Postprint: Modeling and Service Mechanism Design for Collaborative Emergency Intelligence Multi-Agent Systems

Authors: Guo Hua, Qu Fang, Wang Ying, Li Jia

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Abstract

[Purpose/Significance] This study addresses the challenge of agent system architecture and business processes for organizing distributed intelligence services to work collaboratively, facilitating the transition of intelligence services from "node services" to "process-oriented services."

[Method/Process] Employing participatory observation, semi-structured interviews, and deductive reasoning, this research investigates the construction and preliminary validation of principles and mechanisms for emergency intelligence service multi-agent systems in cross-organizational collaboration scenarios.

[Results/Conclusion] Based on case analysis and process deduction, this paper proposes an extended BDI multi-agent model and an intelligence service mapping mechanism, providing a theoretical foundation for the technical framework of emergency intelligence collaborative services.

Full Text

Preamble

Authors: Guo Hua[1],[2], Qu Fang[3], Wang Ying[1], Li Jia[4]
[1]Business School of Hohai University, Nanjing 211100
[2]World Water Valley Institute of Hohai University, Nanjing 211100
[3]Jiangsu Communication Service Company, Nanjing 210006
[4]Business School of Central South University, Changsha 410083

Abstract:
[Purpose/Significance] This study addresses the problem of how to organize distributed intelligence services into a collaborative multi-agent system architecture and business process, promoting the transformation of intelligence services

from "node services" to "process services." [Method/Process] Using participatory observation, semi-structured interviews, and deductive reasoning, this research constructs and preliminarily validates the principles and mechanisms of a multi-agent system for emergency intelligence services in cross-organizational collaboration scenarios. [Result/Conclusion] Based on case analysis and process deduction, an extended BDI multi-agent model and intelligence service mapping mechanism are proposed, providing a theoretical foundation for the technical framework of emergency intelligence collaborative services.

Keywords: intelligence service; emergency intelligence; multi-agent
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Introduction

Most national governments currently adopt a classified management and hierarchical centralization system for emergencies, leading to the fragmentation of intelligence resources and compartmentalization of intelligence services. As an increasing number of emergencies demonstrate complexity and cross-domain characteristics, cross-organizational collaboration has become an essential mode for emergency intelligence services. Relying on either centralized organizational structures or decentralized response frameworks represents two fundamentally different collaboration models. According to synergetics theory, coordinating intelligence services across networked organizations is more effective than maintaining all services within a single centralized framework [1]. Li Yang and Sun Jianjun [2] point out that emergency response is a multi-service entity system for intelligence resource supply and operation. When multiple service entities jointly form an intelligence service network, virtualized collaboration in emergency response can transcend organizational structures and management hierarchies [3]. Daily intelligence interactions among network nodes facilitate interaction between potential collaborative organizations, maintaining them at an effective normal relationship level and enabling them to work collaboratively during emergency states [4].

Coordinating multiple intelligence service entities typically involves integrating databases, information repositories, and knowledge bases, or constructing metasearch engines through domain ontology fusion. These approaches primarily address interoperability issues between different intelligence systems [5], but have not yet resolved the problem of how to organize distributed intelligence services into collaborative system structures and business processes. Multi-agent systems use collaboration among agents to improve individual agent functionality [6], helping to promote the transformation of intelligence services from "node services" to "process services" [7]. Multi-agent systems typically focus on the inter-constructive relationships among agents and the collective environment [8], neglecting the impact of external management organizational relationships and social environments; moreover, for process services, there are operational difficulties in flexibly combining fine-grained intelligence services at the process level. Through participatory observation of typical cases, this paper analyzes and understands the influencing factors and business requirements of intelligence collaborative services, proposes a construction approach for a multi-agent system for emergency intelligence collaborative services, and designs an intelligence collaborative service mapping mechanism by incorporating situational coordination and global strategies into the classical agent model to address event evolution and organizational constraints, ultimately proposing a solution for an emergency intelligence collaborative service multi-agent system.

Literature Review

An agent is an autonomous computing entity that evaluates and adjusts its behavior through perception, and a multi-agent system is a collection of autonomous agents [9]. Multi-agent systems have various organizational models, such as MOISE [10], MOISE+ [11], and AGR [12]. In information science, the BDI agent model based on mental states of belief, desire, and intention [13-14] has been widely applied. The BDI model views a multi-agent system as a collection consisting of a set of beliefs representing the agent' s world model, a set of desires representing potential goals, and a set of intentions representing plans and actions to achieve specific desires. System outputs affect environmental inputs, sequentially updating and indirectly influencing the belief set, desire set, and intention set [15], with its structure shown in Figure 1 [Figure 1: see original paper].

Traditional multi-agent models focus on self-organization within the system [26]. In emergency intelligence collaborative services, strong uncertainty in the external environment (i.e., weak prior conditions) leads to the loss of agency at lower functional levels [27]. To address this issue, Y. Wang et al. [28] proposed using concurrent emotional sets to rapidly achieve communication between system internal and external environments to improve the response speed of the BDI model. F. Meneguzzi and M. Luck [29] proposed using implicit goals to realize agent desires, making the connection between the agent system and external environment closer. A. R. Panisson et al. [30] argued that when changes in the social-level external environment affect changes in the agent' s mental state, structured operational semantics struggle to fully regulate multi-agent systems, requiring the construction of multi-level interaction patterns to distinguish and connect social-level events and agent-level events. Y. Wautelet and M. Kolp [31] analyzed system behavior and internal/external interactions of multi-agent systems at strategic, tactical, and operational levels. S. Mariani and A. Omicini [8] noted that situational coordination within and outside the system has become an important research direction. This means that for emergency intelligence collaborative service multi-agent systems, researchers should not only focus on internal system structures but also understand and master the foundation of environmental construction in real-world contexts.

Case Study

3.1 Case Background

In different types of emergencies and different stages of the same emergency, there are significant differences in emergency intelligence needs and sources, requiring cross-organizational linkage to form interconnected data monitoring and sharing [16-17]. The openness and intelligence of multi-agent systems are suitable for addressing collaboration among emergency intelligence service entities and the autonomy of intelligence networks [18], enabling dynamic aggregation of intelligence resources on-demand by integrating them into emergency scenarios [19]. Feng Zhidong et al. [20] applied multi-agent technology to the emergency field, studying theoretical methods for parallel simulation of mine water inrush and emergency evacuation. Zhang Dinghua et al. [21] studied hybrid simulation technology combining system dynamics and multi-agent technology to explore the dynamic evolution of mass incidents from different levels. L. Yu et al. [22] developed a multi-agent-based emergency information dissemination model to observe and understand the public opinion environment in hazardous chemical leakage emergencies. J. Yu et al. [23] combined multi-agent system technology with multi-criteria evaluation technology for the spatial allocation design of urban emergency shelters. Y. Li et al. [24] used multi-agent systems to construct relationships between humans and the environment, understanding rules for crowd evacuation in flood disaster control. N. Shaikh et al. [25] compared single-agent and multi-agent systems for emergency evacuation simulation schemes in toxic environments, concluding that multi-agent coupling effects are superior.

Dongtai City in Jiangsu Province is one of the pilot cities for national smart city construction, having launched the construction of smart city information infrastructure since 2017. The Dongtai municipal government hopes to improve urban emergency management through the construction and operation of an intelligent emergency intelligence service platform. Dongtai is a county-level city under the jurisdiction of Yancheng City, covering an area of 3,176 square kilometers with a population of 1.0981 million and a GDP of 87.86 billion RMB in 2018, ranking among the top 100 counties in China. The Dongtai emergency intelligence service platform is embedded as a subsystem within the smart city management system, connecting 24 government department information systems through an information sharing and exchange system to provide integrated intelligence services for emergency decision-makers. Taking major fire emergency response as an example, the platform provides intelligence services including: accident location, accident classification, disaster severity assessment, impact scope prediction, affected population prediction, emergency resource location, firefighting rescue plans, traffic control plans, shelter recommendations, green rescue channel design, meteorological information, historical event references, and real-time tracking of on-site situations.

As an integrated intelligence service system, the platform pre-sets certain cross-departmental intelligence collaboration plans. However, in most cases, due to the unpredictable nature, intensity, scope, and complexity of emergencies, limited plans struggle to support emergency decision-making under high uncertainty. The platform coordinates intelligence calls among various departments through a call center and task distribution system, a process with strong uncertainty requiring manual review and approval. While the centralized emergency intelligence service platform has improved the previous lack of global intelligence, its effectiveness still fails to meet requirements for rapid response and dynamic adjustment, representing a common practical dilemma faced by emergency intelligence collaborative services in China.

3.2 Field Investigation

This study employs participatory observation to obtain first-hand data in real contexts. Participatory observation originated from anthropological research on small-scale homogeneous cultures [32], achieving understanding of environmental construction foundations by immersing researchers in participants' natural environments of activities and interactions [33]. During the design phase and trial operation period (August 2019 to July 2020) of the Dongtai emergency intelligence service platform project, three research team members, together with system developers and operation managers, conducted group field investigations in 31 departments and units, participating in system coordination work. They understood these departments' evaluations of current intelligence service status, tracked actual platform operation, and compiled data entries from 108 information systems used by these departments, totaling over 5,000 data items. During the investigation, discussions on cross-departmental emergency intelligence collaboration were recorded, and two emergency management department professionals were interviewed. These discussions and interviews were summarized to observe problems in cross-departmental emergency intelligence collaborative services, with specific content as follows:

Excerpt 1 (Respondent 1, Emergency Management Department):
Respondent: From the emergency management department's perspective, there's no need to connect all departments. First, the workload would be too large, and some information may not be useful. For emergencies with pre-established plans that require multi-department coordination, relevant information systems are connected, but prior negotiation and authorization are needed. For emergencies not under our jurisdiction, we cannot forcibly manage them. Like this pandemic, leadership initially said the emergency management department should handle it. When we interfaced with the health commission, they asked us to report data like infection and confirmed case numbers, which we didn't know.

Excerpt 2 (Respondent 2, Emergency Management Department):
Respondent: Our province currently has 41 emergency special plans, mainly for major incidents with significant impact or special nature requiring multi-department coordination. Currently, information system networking cannot be achieved; our system only handles information reporting and accident informa-

tion submission.

Excerpt 3 (Respondent 3, Information Center):
Researcher: What happens when encountering a new emergency without a pre-established plan?
Respondent: We can refer to similar previous plans or make adjustments based on experience. The leadership group will deliberate and issue an emergency response method suitable for the situation. A mechanism is needed to fully mobilize all departments.

Excerpt 4 (Respondent 4, Park Management Committee):
Respondent: The compartmentalized system leads to endless forms for us at the grassroots level, with various reporting standards. Health and epidemic prevention, community management, and social security are handled by different departments with different information focuses. The most difficult part is coordination among departments.

Excerpt 5 (Respondent 5, Water Affairs Bureau):
Researcher: The information center reported that Water Affairs Bureau data cannot be connected due to confidentiality requirements. Are there technical workarounds?
Respondent: Hydrological intelligence is highly specialized; even if we provide the data, you wouldn' t understand it. How to issue warnings and what risks exist still require our professional judgment.

Excerpt 6 (Respondent 6, Telecom Company):
Respondent: We cannot directly provide user data to the government, but we can provide some calculated services, such as crowd aggregation scale in risk areas during large-scale cultural and sports activities, and mobility indicators during traffic peak hours.

Many departments, including the Water Affairs Bureau and Telecom Company, also emphasized data security issues, such as the Human Resources Bureau, Commerce Bureau, and Urban Management Bureau, all proposing the feasibility of providing intelligence in service form rather than raw data.

3.3 Results Analysis

First, the investigation and interviews reveal that organizational functions, business division, information security, and other factors all affect emergency intelligence collaboration effectiveness. Whether required intelligence can be obtained in a timely manner during emergency response is not merely a technical issue but is also constrained by organizational structures. Second, when facing new types of emergencies without precedent or when emergencies evolve and produce spillover effects, centralized framework-based intelligence collaboration relying on pre-established plans is prone to failure. Finally, intelligence collaboration is not equivalent to data exchange; intelligence services involve service combinations at different levels, requiring coordination among multiple service entities.

Treating intelligence service entities as intelligent agents, multi-agent systems will help resolve the dilemmas of intelligence collaborative services. This requires particular consideration of situational evolution and organizational constraints: (1) Due to different participation requirements for potential intelligence service entities during emergency situational evolution, intelligence collaborative service reasoning is not only a matter of self-organization within the agent system but is more significantly influenced by the external environment, such as spillover effects triggering cross-domain intelligence demands and leading to participation of new intelligence service entities; (2) Due to policy orientation constraints in the emergency management system, agent system service strategies may be dominated by higher-level strategies, causing emergency management departments to prefer intelligence from local systems or traditional intelligence agencies, or to exclude specific intelligence service entities for confidentiality reasons. Additionally, the rapid response required by emergency intelligence services poses significant challenges to multi-agent system reasoning efficiency. The classical BDI agent model cannot specifically address these issues and requires further research and solutions for application in emergency intelligence service scenarios.

Agent Model and Service Mechanism

4.1 Agent Model Construction

Incorporating situational coordination and global strategies into the classical BDI model, this paper designs a new multi-agent system model for emergency intelligence collaborative services: an agent is defined as a first-order logical structure Ag: <Eve, Bel, Pol, Sit, Des, Int>, where Ag is the agent identifier, Eve is the event stack, Bel is the belief set, Pol is the policy set, Sit is the situational interpreter, Des is the desire set, and Int is the intention set.

The event stack is a classified sequence of events reflecting changes in states, beliefs, goals, and tasks, with multiple interrelated events forming the initial conditions for plan invocation. The policy set is the union of global and local policies, where global policies reflect organizational constraints of the intelligence service network, such as selection preferences and policy orientations. The situational interpreter is the mapping of the external environment in the agent system during emergency situational evolution, with its output jointly modifying the belief set together with the internal environment of the agent system. The belief set includes initially set meta-beliefs and interpretations of the agent system' s internal environment. The desire set selects goals to be achieved based on belief updates, with goal selection constrained by policies. The intention set includes plan libraries and actions, achieving desires through agent actions, with plan formulation also achievable through implicit goals triggered by event states. Extending the classical agent model, the internal structure of the extended BDI agent is shown in Figure 2 [Figure 2: see original paper].

Thus, situational coordination becomes a closed-loop process. Agents perceive emergency evolution information from the objective world, map external environment states to beliefs through situational identification and interpretation, and execute reasoning processes under global policy constraints to select predefined plans or generate new plans based on situational matching of implicit goals. Agent actions affect both the multi-agent system itself and the external system environment through management activities, thereby influencing global policy selection and constraining individual agent desires. Constructing a meta-model for emergency intelligence service multi-agents can coordinate business interactions and positional interactions among nodes in the intelligence service network, as shown in Figure 3 [Figure 3: see original paper].

4.2 Service Mapping Mechanism

Emergency intelligence service entities have differentiated service capabilities and provide different service content. In different business scenarios, the same intelligence service entity can be in a position to provide integrated services, be integrated into services, or be temporarily adjusted out of the intelligence service network. Considering emergency management departments' selection preferences and decision-making contexts, the service aggregation logic of the multi-agent system will adaptively change after intelligence tasks are triggered. Intelligence tasks can be progressively decomposed into semantic logic at the user level, business processes at the system level, and fine-grained intelligence service resources at the resource level. The intelligence service network needs to achieve penetrative invocation of underlying intelligence service resources in heterogeneous network environments through certain mapping mechanisms. A two-level mapping model of process and resource is adopted to aggregate emergency intelligence services, as shown in Figure 4 [Figure 4: see original paper].

In process logic mapping, dynamic variable nodes are used to transform customized services in specific contexts into user business processes and match or update plans. In service resource mapping, service invocation chains are constructed to combine fine-grained intelligence service resources among or within agents. Since there are intelligence services that can complete similar tasks with the same willingness, the construction of service invocation chains must consider non-functional attribute preferences, including service quality, real-time requirements, and organizational constraints (such as agent selection preferences and prior paths between agent nodes). The emergency intelligence service aggregation process is shown in Figure 5 [Figure 5: see original paper].

Fine-grained intelligence services are defined as S, and service invocation behavior I consists of a characteristic vector sextuple {InvokeID, Si, Sj, F, Agi, Agj}. Where InvokeID represents the invocation request, Si represents the service requesting invocation, Sj represents the invoked service, F represents the invocation method or function, Agi represents the agent requesting the service, and Agj represents the agent providing the service. The service invocation chain corresponding to a specific intelligence service business process consists of all participating invocation behaviors and agents, i.e., LinkID = (I_1, ···, I , ··· , I , Agc). Where LinkID represents the service invocation chain, I represents the i-th service invocation behavior in the chain, and Agc represents the agent providing integrated intelligence services to the end user (i.e., the emergency management department issuing the intelligence task).

Intelligence Collaborative Service Verification

5.1 Data Sources

This study uses the data resource set of the Dongtai emergency intelligence service platform as the primary data source to verify intelligence collaborative services supported by the multi-agent system. The simulated environment includes data from 31 information systems across 14 departments, which are intelligence sources directly related to urban emergency management, as shown in Figure 6 [Figure 6: see original paper]. For lower-level fine-grained intelligence services and business data not covered by existing data, simulated data sources are constructed.

A front-end agent pattern is used to invoke services, with the process of calling intelligence services through the backend shown in Figure 7 [Figure 7: see original paper].

5.2 Simulated Business Scenario

Since Dongtai lacks major cross-organizational, cross-domain emergency cases, the "3·21" chemical plant explosion accident in Xiangshui, Jiangsu, a prefecture-level city in the same region, is used to reconstruct the business scenario. This incident, caused by a major safety production accident, generated emergency intelligence demands including production safety, environmental protection, medical rescue, and transportation. Based on secondary data analysis (government documents, situation reports, and news reports) by L. Du et al. [37], the emergency response is divided into four stages: T_1 Accident outbreak stage (March 21 incident), T_2 Fire control stage (March 21-22), T_3 Search and rescue completion stage (March 23-25), and T_4 Recovery and disposal stage (March 26-27). Each stage has different emergency management functional requirements and involves new emergency management organizations, as shown in Figure 8 [Figure 8: see original paper].

5.3 Dynamic Organization of Intelligence Services

In different stages of emergency evolution, the global strategy of emergency intelligence services changes with varying emergency management priorities. Situational evolution alters global strategies, which together constitute the external environment of the emergency intelligence service multi-agent system. While multi-agent systems have internalized beliefs, desires, strategies, and intentions, the positions and relationships among network nodes are directly affected by the external environment, with intelligence service organization showing dynamic development. According to the extended BDI model, the emergency intelligence service multi-agent system Ag-net is defined as: $\{Ag_0, Ag_1, Ag_2, \cdots, Ag\ \}$, with each agent providing domain-specific intelligence services.

Before emergencies occur, each intelligence service entity provides services to its superior department in a single-agent form, lacking networked business logic for intelligence services, with beliefs obtained through prior paths reflecting the reality of isolated operations. After emergencies occur, with the establishment of on-site command posts and intelligence service networks, different types of intelligence service entities join sequentially, changing the internal environment of the agent system. Ag_0 becomes the integration agent directly providing intelligence services to the command post. In different stages of emergency evolution, as intelligence tasks, event contexts, and organizational relationships change, the intelligence service network Ag-net dynamically adjusts positions and relationships among agents according to global strategies and action plans, completing required business processes and invoking corresponding fine-grained service resources. The organization process is shown in Table 1 .

Taking the intelligence service process for secondary accident disposal plans generated in stage T_2 as an example, the agent implementation mechanism and collaborative service path are illustrated. The multi-agent system and users agree to use Ag_0 as the integration agent for all intelligence services. Users obtain the intelligence service catalog and propose intelligence tasks, namely how to prevent and handle secondary accidents. This task can be further decomposed into two sub-tasks: preventing secondary explosions and handling environmental pollution disasters. At the business logic level, these sub-tasks are further decomposed to obtain fine-grained intelligence service requirements and their relationships, including situational interpretation of the explosion site, types and scales of hazardous chemicals stored in the involved enterprise and chemical park, atmospheric/water/soil monitoring and prediction data, and location-based socioeconomic information. These business requirements are mapped onto the system process plane to form fine-grained intelligence service combinations. Under the premise of satisfying service entity selection preferences and non-functional requirements such as service quality and real-time performance, the multi-agent system provides emergency intelligence collaborative service results, with the process constrained by event contexts and institutional constraints represented by users. The virtual network formed by the intelligence collaborative service process is neither a centralized star network nor a tree network, but rather a combination of centralization and decentralization based on task requirements and global strategy selection.

Treating each system component as an instance of templates for agents, plans, beliefs, desires, and strategies provided by the multi-agent model, Figure 10 [Figure 10: see original paper] describes part of the multi-agent system structural design. Among them, Ag_0 and Ag_3 are the integration agent for all services and the intermediate agent for secondary accident emergency plan integration, respectively, both occupying relatively important positions in the intelligence collaborative service shown in Figure 9. If an agent cannot complete the intelligence task proposed by the user, it can choose to refuse service or request to change its position in the intelligence service network when sending service decisions.

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Author Contributions

Guo Hua: Research framework design and paper writing;
Qu Fang: Multi-agent prototype system process and mechanism design modification;
Wang Ying: Participatory observation, semi-structured interviews, and survey analysis;
Li Jia: Participatory observation, semi-structured interviews.