Towards Self-Organising Global Supply Chains in the Internet of Things

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ABSTRACT

Current supply chain management software architectures, although distributed, typically put decision making and control at the centre of the network. Such architectures do not scale well with increasing complexity, dynamism and volume of available business information from the so-called "Internet of things". In this paper, we investigate highly decentralised and self-organising middleware architectures for global supply chain management. We propose to model supply chains as collections of cooperating/competing agents that represent smart artefacts, services, and/or business processes. We outline the key requirements to be addressed in order to support this decentralised self-organising network of agents governed by high-level policy specifications.

Keywords

Self-organisation, decentralised supply chains, optimisation, service bus.

1. INTRODUCTION

Future global supply chain management strategies should be able to avail of an increasingly rich supply of information coming directly from the systems and artefacts that make up the supply chain [5,13]. That information will be needed to improve strategic decision making, to adapt operational decisions to changing circumstances, to improve agility in the face of merger and acquisition, and, at a high level, to address the "pain points" such as the avoidance of underutilised resources, identification of counterfeit products, or compliance with regulatory guidelines that have been identified by businesses [14, 17, 25] as existing in current global supply chains. Underlying this business vision is a technology vision of a world in which sensing, as well as processing and communications capability is routinely integrated into the systems and artefacts that constitute supply chains ranging in granularity from individual products to the vehicles used to transport them and potentially providing precise information about their current state and context, even in real time across the planet. This is the so-called "Internet of Things" [1, 20].

One challenge is to deliver appropriate software architectures and services that can both allow this vast information resource to be accessed effectively. Another is to facilitate the deployment of business processes that can take advantage of the availability of this information to dynamically monitor, adapt, optimise and control the supply chain.

Current supply chain management software architectures, although distributed, typically put decision making and control at the centre of the network [6,9]. Such architectures do not scale well with increasing complexity, dynamism and the volume of business information available from a variety of sources. Such architectures are unlikely to be able to exploit the opportunities for local decision making afforded by the distribution of sensing and processing capabilities over the components of the supply chain. They are typically rigid and brittle, and consequently inappropriate for future supply chain management. Moreover, the few middleware that have been developed for the Internet of Things so far focus on low-level sensing and processing of information from the physical world and do not provide high-level abstractions suitable for the next generation of supply chains [2]. To address the challenges posed by the management of future global supply chains, we are investigating a highly decentralised and self-organising middleware architecture for global supply chain management supporting processing of information and decentralised decision making close to the point at which they are relevant.

State-of-the-art distributed systems research is increasingly applying decentralised self-organising techniques to large-scale complex problems involving millions of cooperating/competing entities [4, 11]. Experience indicates that a successful solution to these problems involves pushing intelligence to the edges of these large networks. In this paper, we therefore propose to model next-generation global supply chains as collections of cooperating/competing agents based on the sentient object paradigm [18] potentially representing "smart" artefacts (i.e., those with embedded sensing and processing capabilities), services, and/or business processes. We will then focus on key requirements to support the information flow between and real-time coordination of agents to transform the global supply chain into a decentralised self-organising network of agents governed by high-level policy specifications.

The paper is structured as follows. In Section 2, we present our decentralised middleware architecture for self-organising global supply chains. In Section 3, we discuss the key requirements to support such supply chains. We conclude in Section 4.

2. DECENTRALISED MIDDLEWARE ARCHITECTURE

In the middleware architecture that we propose, global supply chains are modelled as collections of loosely and tightly coupled business processes operating at all levels in the global "enterprise" to accomplish business goals. A business process is modelled as a collection of agents that collectively implement business objectives and management decisions. The individual agents will be designed following the sentient object paradigm, an agent model designed for the development of large-scale ubiquitous computing applications and which therefore provides a natural abstraction for the global supply chain domain. The sentient object model provides support for managing information flows from sensor infrastructure or business services, it provides reasoning algorithms that support action selection strategies aligned to business goals even in the presence of conflicting or partial information on the business domain, and, finally, it provides a platform for the automated management of tasks along the stages of a global supply chain. Decoupling constituent business processes from global supply chains in this way and modelling the collaborative interaction between them provides the basis for highly dynamic, distributed but coordinated decision making in the presence of an uncertain environment.

This decentralised approach to global supply chain management provides opportunities to enterprises to deploy new management techniques and to support adaptive and timely response to the dynamic and rapidly changing environment in which business is conducted. The challenge from a technology perspective is to combine existing business "know-how" and best practices with the new opportunities provided by the ever-increasing information flows that characterise the sensor-rich environments in which business now operates. There exists the potential for novel algorithms combining business domain knowledge with sensor data flows and optimisation and planning theory. We propose a collaborative optimisation framework that allows sentient objects to exploit the characteristics of global supply chains and which provides novel algorithms to allow a decentralised optimisation strategy to learn new behaviour and to make use of existing business domain knowledge. These algorithms will play an important role in enabling the different components of an optimisation strategy to be adapted to the currently available information about the business process. Examples of such components include the state representation of an environment and the action selection strategies that are followed by agents to act on their environment.

Interconnecting the components of the global supply chain, whether they be sentient objects (representing tasks of a business processes, collections of artefacts, or offered services), or legacy applications, represents a further challenge. Architecturally, our approach is to deliver an Enterprise Service Bus providing the communication channel between connected components and offering services such as service discovery and message routing, dynamic binding, filtering at different levels of granularity and management of quality of service. The resulting federated architecture is depicted in Figure 1.

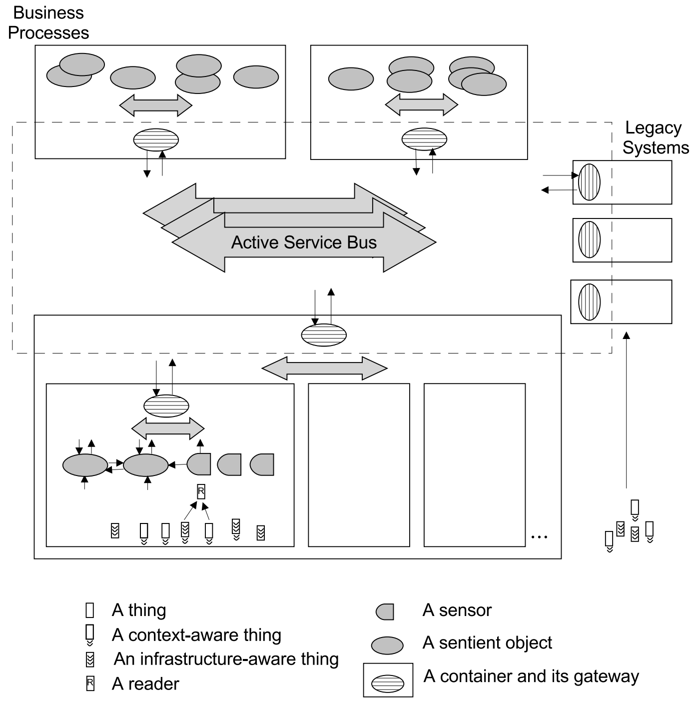

Figure 1: Overall software architecture

3. KEY REQUIREMENTS

In this section, we identify the services and techniques necessary for the construction of a decentralised middleware architecture for self-organising global supply chains.

3.1 Decentralised Business Process Modelling

Business Process Modelling is a vital task since business models provides a bridge between the business domain and supply chain management infrastructure [3, 10]. To ensure success, the business models should represent the entirety of the global supply chain structure from business objectives, key actors and work practices to constraints and "business know-how" as well as business policy. Moreover, business process modelling must address the integration of data from diverse sources.

Our approach is to represent active business processes as collections of agents. Thus the information encoded in the model must be mapped into the software agents (sentient objects) that are responsible for the execution of the business process including the instantiation of decentralised coordination and optimisation strategies to mediate the collaboration and competition between coexisting business processes based on policy specification.

In order to apply this approach, business process modelling tools are required to capture information on the business process and its domain, as well as tools to parse this specification to establish the characteristics of the business domain such as the quality of available sensor data and, crucially, the degree of domain-specific knowledge that is available to optimisation algorithms. This specification can then be used in a strategy selection engine which provides a mapping between the mathematical properties of planning and optimisation algorithms and the requirements and characteristics of the business process domain. A suitable strategy will be chosen from the library of optimisation algorithms available and that algorithm will be seeded with the set of system states and goals derived from the business "know-how" encoded in the process specification.

3.2 Optimisation and planning techniques

Global Supply Chain Management systems exhibit stochastic, dynamic, and complex behaviour in the presence of partial observability. Partial observability stems from the dependence on sensor data for determining the current status of the business process with the attendant possibility of error or partial coverage in the sensor readings. The sensor platform sits between the system and the domain thereby precluding full observability and global knowledge. The stochasticity and dynamism of global supply chains stems from events that can occur that are outside of management control, for example, traffic accidents while transporting goods or industrial relation disputes.

Classical optimisation and planning algorithms such as state and plan-space planning assume finite state space representations, fully observable environments, deterministic state transitions, and static environments [8]. More sophisticated optimisation techniques such as those based on Markov Decision Processes (MDPs) and Partially Observable MDPs (POMDPs) can be extended to uncertain environments but cannot scale to complex real-world problem sizes such as global supply chain management [16]. Methods such as Genetic Algorithms and Reinforcement Learning techniques are unsuitable when applied to global supply chains due to their centralised formulation and requirement for global knowledge [19, 21].

To improve the efficiency of global supply chain management, applying decentralised algorithms for optimisation and planning is necessary. Based on our experience of using stochastic algorithms in distributed systems, we are proposing to use Collaborative Reinforcement Learning (CRL), a decentralised optimisation framework [7], that accurately reflects the distributed and partially observable characteristics of a global supply chain and which is flexible enough to operate across a diverse communications and sensor infrastructure.

CRL is an online optimisation technique for distributed systems that has been shown to perform well in areas that exhibit a lack of global knowledge about the overall system such as Mobile Ad-Hoc Networks (MANET) routing or load balancing [7]. However CRL assumes that state determination is noiseless and state transitions are deterministic. As developed, CRL is a self-organising unsupervised learning technique and attempts to adapt its behaviour to its environment. Applying CRL in global supply chains will require it to be extended in three main ways to exploit knowledge about the underlying sensor and communication infrastructure and to integrate the expertise of a domain expert, to support the implementation of multiple simultaneous and potentially competing policies, and to address partially observable environments, for example, by incorporating ideas from POMDPs.

3.3 Active Service Bus

To support self-organising global supply chains, any middleware communication architecture must overcome a number of challenging problems. With the emergence of the so-called "internet of things", next-generation global supply chains will have access to a much larger volume of diverse information about an increasing number of resources available in support of different aspects of a global supply chain. Available information will range from high-level strategic business information to fine-grained sensor information. Access to such a volume of information poses a significant challenge to the communications infrastructure in terms of scalability, fidelity, addressing and routing. Secondly, the infrastructure will need to provide access to a dynamic ecosystem of business services potentially existing across multiple administrative domains. Finally, the middleware architecture should support the inherent heterogeneity, for example, in terms of computational power, communication latency/bandwidth and diverse QoS constraints, present in the global supply chain IT infrastructure.

To address these challenges, a communication middleware architecture that adopts the highly-scalable, backwardly compatible Service Bus abstraction is necessary. The Service Bus abstraction will be designed as a Publisher/Subscriber (Pub/Sub) system [12] structured as a hierarchy of quality-of-service (QoS) containers each incorporating an instantiation of the Service Bus providing an appropriate QoS for intra-container communication and federated to form a global infrastructure via gateways. At higher levels containers will expose loosely-coupled services communicating with each other and at lower levels will represent individual wireless sensor networks. The architecture is designed to allow scaling up from individual sensor networks to a global Internet-based Pub/Sub system and providing interoperation with existing middleware standards such as WSDL/SOAP [24] for access to legacy systems.

To deliver the Service Bus requires enhancements to state-of-the-art Pub/Sub communication systems to overcome the challenges outlined in the above paragraphs. One of the main research challenges is the design of a scalable (in terms of its geographical dispersion, the number of connected publishers and subscribers and the volume of published information) Pub/Sub system. This challenge may be tackled by leveraging existing techniques from the Peer-to-Peer communication paradigm such as Distributed Hash Tables [15, 22] in combination with active networking techniques [23] allowing the deployment of agents implementing intelligent filtering, data fusion, and data conversion into the Bus infrastructure. The resulting Service Bus will not merely be a passive communication channel but an Active Service Bus embedding appropriate information processing. Similar techniques can be used to support service composition and selection (in accordance with a variety of constraints such as trust, QoS, etc.), and automatic gateway generation, in particular, to support access to legacy systems.

4. CONCLUSIONS

In the coming decades, a strategic area for the Internet of Things will be global supply chain management. In this paper, we proposed a decentralised middleware architecture for self-organising global supply chain management. We identified the key requirements to be addressed to support such global supply chains and outlined promising approaches. We are currently investigating these ideas in our ongoing research.

Acknowledgments

The authors are grateful to their colleagues in the Business School of Trinity College Dublin, the IBM Wireless and RFID Centre of Excellence in Dublin, Bell Labs Research Alcatel-Lucent, and the Knowledge and Data Engineering Group of Trinity College Dublin, for discussions during the course of this work.

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