A Multi-Agent System for Enterprise Integration

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ABSTRACT

This paper presents a real-world application of a multi-agent system to enterprise integration for manufacturing planning and execution. The production management system used by most manufacturers today is comprised of disconnected planning and execution processes, and lacks the support for interoperability needed for enterprise wide integration. This situation often prevents the manufacturer from fully exploring market opportunities in a timely fashion. To address this problem, we propose an agent-based framework for intelligent enterprise integration. A set of agents with specialized expertise can be quickly assembled to help with the gathering of relevant information and knowledge, to cooperate with each other and with other parts of the management system and humans to arrive at timely decisions in dealing with various enterprise scenarios. The proposed multi-agent system, including its architecture and implementation are presented. The work of this system is demonstrated through an example integration scenario involving real management software systems.

1. Introduction

The production management system used by most of today's manufacturers consists of a set of separate application softwares, each for a different part of the planning, scheduling, and execution processes [17]. For example, Capacity Analysis (CA) software determines a Master Production Schedule that sets long-term production targets. Enterprise Resource Planning (ERP) software generates material and resource plans. Scheduling software determines the sequence in which shop floor resources (people, machines, material, etc.) are used in producing different products. Manufacturing Execution System (MES) tracks real-time status of work in progress, enforces routing integrity, and reports labor/material claims.

Most of these business applications are legacy systems developed over years. Although each of these software systems performs well for its designated tasks, they are not equipped to handle complex business scenarios, especially those which represent exceptions to the normal or expected business processes and whose resolution involve several applications. For example, consider the scenario involving a delay of the shipment date on a purchased part. This event may cause one of the following possible actions: (a) the manufacturing plan is still feasible, no action is required; (b) order substitute parts; (c) reschedule; or, (d) reallocate available material. To determine which of these actions to take, different applications (e.g., ERP and Scheduler) and possibly human decision-makers must be involved. Examples of other similar scenarios include a favorite customer's request to move ahead the delivery date for one of its orders, a machine break-down being reported by MES, a crucial operation having its processing rate decreased from the normal rate, to mention just a few. Timely solutions to these and other scenarios are crucial to agile manufacturing. Unfortunately, current production management systems cannot support integrated solutions to such scenarios. This is because existing management systems provide little interoperability among isolated individual application softwares, and there is no software to coordinate information and knowledge gathering and decision-making at the enterprise level [1,16].

With matching funds from the National Institute of Standards and Technology of the U. S. government, the *Consortium for Intelligent Integrated Manufacturing Planning-Execution* (CIIMPLEX), consisting of several private companies and universities, was formed to address this problem. The aim of the consortium is to develop technologies for intelligent enterprise-wide integration of planning and execution for manufacturing [3]. One approach to this problem might be to re-write all application softwares into a monolithic integrated planning-execution system capable of handling all foreseeable scenarios. This approach is unfeasible because: (a) re-writing legacy application systems is formidably expensive; (b) a monolithic system is too rigid to expand to cover unforeseen new scenarios once the system is put into use; and (c) unlike distributed systems, a monolithic system is difficult to develop, to test, and to maintain. Instead, CIIMPLEX adopts as one of its key technologies the approach of intelligent software agents, and develops a multi-agent system (MAS) for enterprise integration.

In sharp contrast to traditional software programs, software agents are programs that help people solving problems by collaborating with other software agents and other resources in the network [2,4,14]. For instance, individual software agents can be designed to perform data collection and analysis of plans and schedules, to keep constant vigil against mismatches among these plans and schedules at different levels of abstraction and time horizons. Other agents can be designed to resolve the conflicts either by themselves or in coordination with human managers and analysts. Personal assistant agents can be designed to assist human managers/analysts. Still other agents can be created to provide communication and other capabilities to the legacy systems so they can effectively communicate to each other and to other agents. Manufacturing planning and execution can thus be integrated through the collaboration of these agents, and various business scenarios can be resolved faster and more cost-effectively.

The rest of this paper is organized as follows. In the next section, we briefly describe the software agent technologies that are relevant to the task of manufacturing integration. Sections 3 and 4 are the core of this paper where we first present the proposed multi-agent system's architecture, and then its function through an example scenario. In Section 5 we conclude the paper with discussions of ongoing work to expand the agent system, and the directions for future research.

2. Multi-Agent System and Agent Collaboration

There is no consensus on the definition of software agents or of agency, and some people go so far as to suggest that any piece of software or object that can perform a specific given task is an agent. However, the prevailing opinion is that an agent may exhibit three important general characteristics: *autonomy*, *adaptation,* and *cooperation* [10,13]. By "autonomy" we mean that agents have their own agenda of goals and exhibit goal-directed behavior. They are not simply reactive, but can be pro-active and take initiatives, as they deem appropriate. In this sense, agent systems can be viewed as a generalization of the client-server model in that each agent can be both a client and a server and can provide and request services to and from others. Adaptation implies that agents are capable of adapting to the environment, which includes other agents and human users, and can learn from the experience in order to improve themselves in a changing environment. Cooperation and coordination between agents is probably the most important feature of MAS [13]. Unlike those stand-alone agents, agents in a MAS collaborate with each other to achieve common goals. In other words, these agents *share* information, knowledge, and tasks among themselves. The intelligence of MAS is not only reflected by the expertise of individual agents but also exhibited by the emerged collective behavior beyond individual agents. From software engineering point of view, the approach of MAS is also proven to be an effective way to develop large distributed systems. Since agents are relatively independent pieces of software interacting with each other only through message-based inter-agent communication, system development, integration, and maintenance become easier and less costly [11]. For instance, it is easy to add new agents into the agent system when needed. Also, the modification of legacy applications can be kept minimal when they are to be brought into the system

Cooperation and coordination of agents in a MAS requires agents to be able to understand each other and to communicate effectively with each other. The infrastructure that supports agent cooperation in a MAS is thus seen to include at least the following key components.

- A common agent communication language (ACL) and protocol.
- A common format for the content of communication.
- A shared ontology.

In CIIMPLEX we choose the Knowledge Query Manipulation Language (KQML) as a communication language and protocol; the Knowledge Interchange Format (KIF) as the format of the communication content; and the concept of a shared ontology [15]. In what follows we briefly describe the three components and justify their selections in the context of manufacturing integration environment.

2.1. KQML

KQML is a message-based ACL [6,7,15], and it considers each message not only contains the content but also the attitude or “intention” the sender has for that content. For instance, consider that Agent *A* sends the following statement as the content of a message to Agent *B*:

“the processing rate of operation 1 at machine X is greater than 5.”

Agent *A*, in different circumstances, may have different intentions about this statement. Agent *A* may simply *tell B* that this statement is true in its own database, or *ask if* this statement is true in *B*’s database; or attaches some other intention to this statement. KQML provides a formal specification for representing the intentions of messages through a set of pre-defined *performatives* used in the messages. A subset of KQML performatives that are particularly relevant to our agent system include *ask-one, tell, advertise, subscribe, recommend-one, error, sorry, etc.*

A KQML message is thus divided into three layers: the content layer, the communication layer, and the message layer. The content layer bears the actual content of the message, in a language chosen by the sending agent. The communication layer encodes a set of features to the message to describe the lower level communication parameters such as the identity of the sender and recipient, and a unique identifier associated with the communication. The message layer encodes the message, including its intention (by a chosen performative), the content language used, and the ontology. The syntax of KQML messages is based on a balanced parenthesis list whose first element is the performative and the rest are the parameters in the form of keyword/value pairs. The following is an example of an actual KQML message sent by agent “joe” to agent “stock-server”, inquiring about the price of a share of IBM stock where ?x is an uninstantiated variable. The reader is referred to [7] for the detailed description of KQML specifications.

```
(ask-one
    :language      KIF
```

```
        :content       (Price IBM ?x)
        :sender        joe
        :receiver      stock-server
        :reply-with     zxcasd
    )
```

2.2. KIF

Although KQML allows agents to choose their own content language, it is beneficial for all agents within one MAS to exchange most if not all of their messages in a single neutral format. One obvious advantage of adopting a common content format is efficiency. Instead of many-to-many format conversion, each agent only needs to convert the content of the message between its own internal representation and the common format. KIF (Knowledge Interchange Format), due to its rich expressive power and simple syntax, is probably the most widely used neutral message format for agent communication.

KIF is a prefix version of First Order Predicates Calculus (FOPC) with extensions to support non-monotonic reasoning and definitions [9,15]. The language description includes both specifications for its syntax and for its semantics. Besides FOPC expressions of facts and knowledge, KIF also supports extra-logical expressions such as those for the encoding of knowledge about knowledge and of procedures.

2.3. Shared ontology

Sharing the content of formally represented knowledge requires more than a formalism (such as KIF) and a communication language (such as KQML). Individual agents, as autonomous entities specialized for some particular aspects of problem solving in a MAS, may have different models of the world in which objects, classes and properties of objects of the world may be conceptualized differently. For example, the same object may be named differently ("machine-id" and "machine-name" for machine identification in databases of two agents). The same term may have different definitions ("salary-rate" referring to hourly rate in one agent and annual rate in another). Also, different taxonomies may be conceptualized from different perspectives by individual agents.

Therefore, to ensure correct mutual understanding of the exchanged messages, agents must also agree on the model of the world, at least the part of the world about which they are exchanging information with each other. In the terminology of the agent community, agents must share a common ontology [15]. An ontology for a domain is a conceptualization of the world (objects, qualities, distinctions and relationships, etc. in that domain). A shared or common ontology refers to an explicit specification of the ontological commitments of a group of agents. Such a specification should be an objective (i.e., interpretable outside of the agents) description of the concepts and relationships that the agents use to interact with each other, with other programs such as legacy business applications, and with humans. A shared ontology can be in the form of a document or a set of machine interpretable specifications.

2.4. Agent collaboration

With a common communication language, a common content language, and a shared ontology, agents can communicate with each other in the same manner, in the same syntax, and with the same understanding of the world. In addition to these three essential ingredients, some service agents are often created in MAS to make agent collaboration more efficient and effective. One type of a service agent is the *Agent Name Server* (ANS). The ANS serves as the central repository of physical addresses for all involved agents. It maintains an address table of all registered agents, accessible through the agents' symbolic names. Newly created agents must register themselves with the ANS with their names, physical addresses and possibly other information by sending to the ANS a message with the performative *register*. (As a presumption, every agent in the system must know the physical address of the ANS.) The ANS maps the symbolic name of a registered agent to its physical address when requested by other agents.

Another type of a service agent is the *Facilitator Agent* (FA) which provides additional services to other agents. A simple FA is a *Broker Agent* (BA). The BA serves, to some extent, as a dynamic information hub or switchboard. It registers services offered and requested by individual agents and dynamically connects available services to requests whenever possible. Agents register their available services by sending BA messages with the performative *advertise*, and request services by sending to the BA messages with brokering performatives such as *recommend-one*. In both cases, the description of the specific service is in the content of the message. In a reply to a *recommend-one* message the BA will send the symbolic name of an agent which has advertised for being able to provide the requested service at the BA, or *sorry* if such request cannot be met by current advertises.

One of the key objectives of CIIMPLEX is to establish a monitoring/notification architecture for the enterprise integration [5]. In this architecture, an application will define events it is interested in (e.g. changes in process rates, yield, material due dates) and have agents to monitor such events. When those events occur, the agents will notify the concerned applications. A natural way to implement the monitoring/notification architecture is to use broker agents to track the agents which can provide monitoring service for a type of event another agent is interest in.

3. CIIPLEX Agent System Architecture

In this section, we describe the MAS architecture that supports inter-agent cooperation in the CIIMPLEX project, with the emphasis on the agent communication infrastructure. Figure 1 below gives the Architecture of the MAS for CIIMPLEX enterprise.

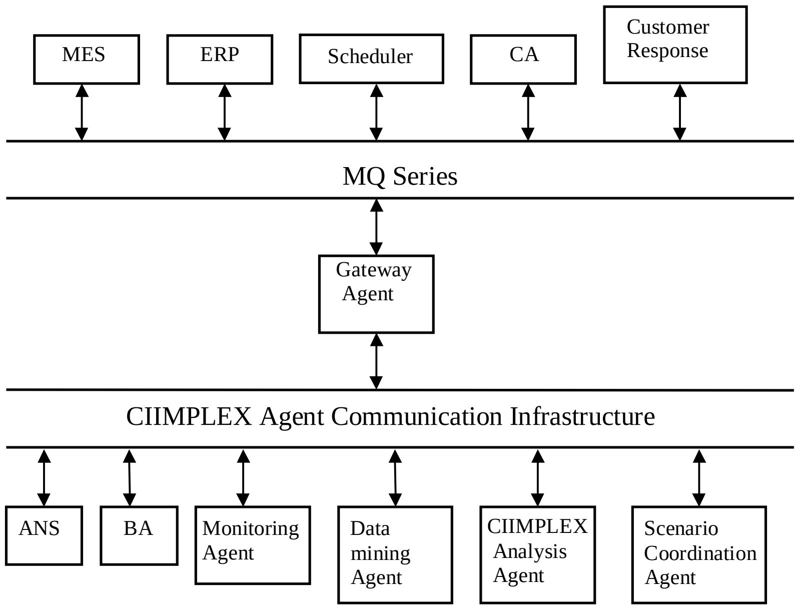


Figure 1. CIIMPLEX Integration Architecture

Besides the service agents ANS and BA, several other types of agents are useful for enterprise integration. For example, data-mining/parameter-estimation agents are needed to collect, aggregate, interpolate and extrapolate the raw transaction data of the low level (shop floor) activities, and to make this aggregated information available for higher level analyses by other agents. Event monitoring agents monitor, detect, and notify about abnormal events that need to be attended. The *CIIMPLEX Analysis Agents* (CAA) evaluate disturbances to the current planned schedule and recommend appropriate actions to address each disturbance. And the *Scenario Coordination Agents* (SCA) assist human decision making for specific business scenarios by providing the relevant context, including filtered information, actions, as well as workflow charts.

All these agents speak KQML, and use a subset of KIF that supports Horn clause deductive inference as the content language. TCP/IP is chosen as the low-level transport mechanism for agent to agent communication. The shared ontology is an agreement document established by the application vendors and users and other partners in the consortium. The agreement adopts the format of the *Business Object Document* (BOD) defined by the *Open Application Group* (OAG). BOD is also used as the message format for communication between applications such as MES and ERP, and between agents and applications. Different transport mechanisms (e.g., MQ Series of IBM and VisualFlow of Envisionit) are under experimentation for communication to and from applications. A special service agent, called the *Gateway Agent* (GA), is created to provide interface between the agent world and the application world. GA's functions, among other things, include making connections between the two transport mechanisms (TCP/IP and MQ Series) and converting messages between the two different formats (KQML and BOD).

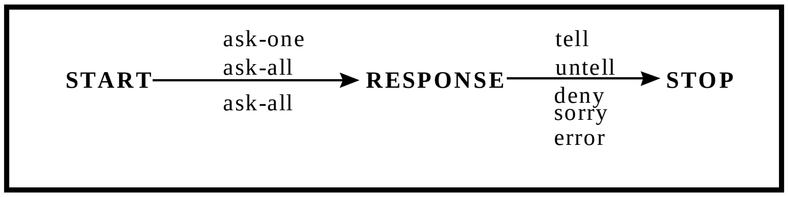
The agent system architecture outlined above is supported by the agent communication infrastructure called *Jackal* developed by the consortium. As indicated by the name, *JACKAL* is written in *J*ava to support *A*gent *C*ommunication using the *K*QML *A*gent communication *L*anguage. The decision to select Java as the implementation language was based mainly on its inter-platform portability, its networking facilities, and its support for multi-thread programming. The next two subsections provide detailed description of Jackal.

3.1. Conversation policies in Jackal

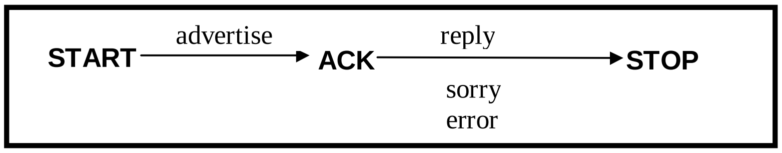
KQML itself only defines the syntax of the language. However, a good, workable semantics is imperative for conducting coherent conversation among agents. To support both syntactic and semantic aspects of the language, Jackal takes a semantic interpretation of KQML from [12] and realizes part of it as a set of conversation policies. In what follows, we first discuss the conversation policies and then the architecture of Jackal.

The conversation policies are procedures which, based on the performatives involved, specify how a conversation (consisting of a sequence of messages) is to start, to proceed, and to terminate. For example, a conversation started with an *ask-one* message will terminate as soon as the sender receives a proper reply. (Possible replies include an *error* message, indicating that the format of the message is incorrect, a *sorry* message, indicating that the receiver cannot provide an answer to the question, or a *tell* message whose content contains an answer to the given question). A conversation started by a message with performative *subscribe* would have a different policy. When Agent *A* starts such a conversation with Agent *B*, the conversation remains open with *A* keeping listening for new messages from *B* that satisfy the subscription criterion.

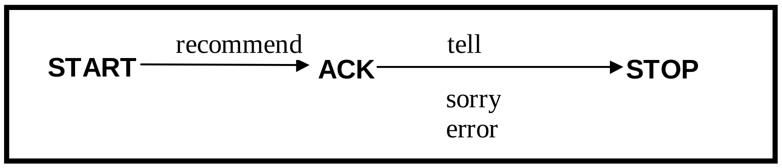
Conversation policies chosen for Jackal can be described using a *Deterministic Finite Automata* (DFA) model. In this model, each conversation starts with a state called **START**, and ends with a state called **STOP.** A conversation moves from one state to another according to the given state transition diagram. The following are the state transition diagrams for some example conversations selected for the CIIMPLEX agent system. In these diagrams, bold upper case character strings are for the states, arcs are for the state transitions, and the lower case strings attached to arcs are for the conditions (inputs) that cause the transitions to occur. For example, in the diagram for *subscribe* conversation, the conversation goes from the initial state, **START,** to a state called **SUBSCRIBE** when an agent issues a message with the *subscribe* performative. The conversation remains at this state until an input (a reply message to the *subscribe* message) is received. If the input is a message with the performative *tell*, the conversation does not change its state (i.e., it loops back to the current state and waits for new messages). If the input is one of the performatives *deny*(*subscribe*), *sorry,* or *error,* then the conversation goes to the state **STOP**, and terminates there.



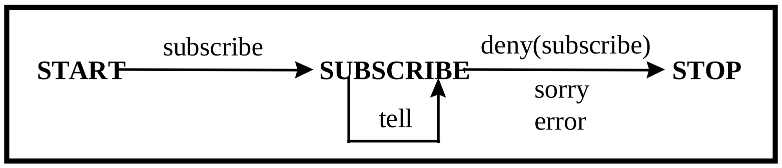
DFA state transition diagram for *ask*- conversations.



DFA state transition diagram for *query/acknowledge* conversations.



DFA state transition diagram for *recommend*- conversations.

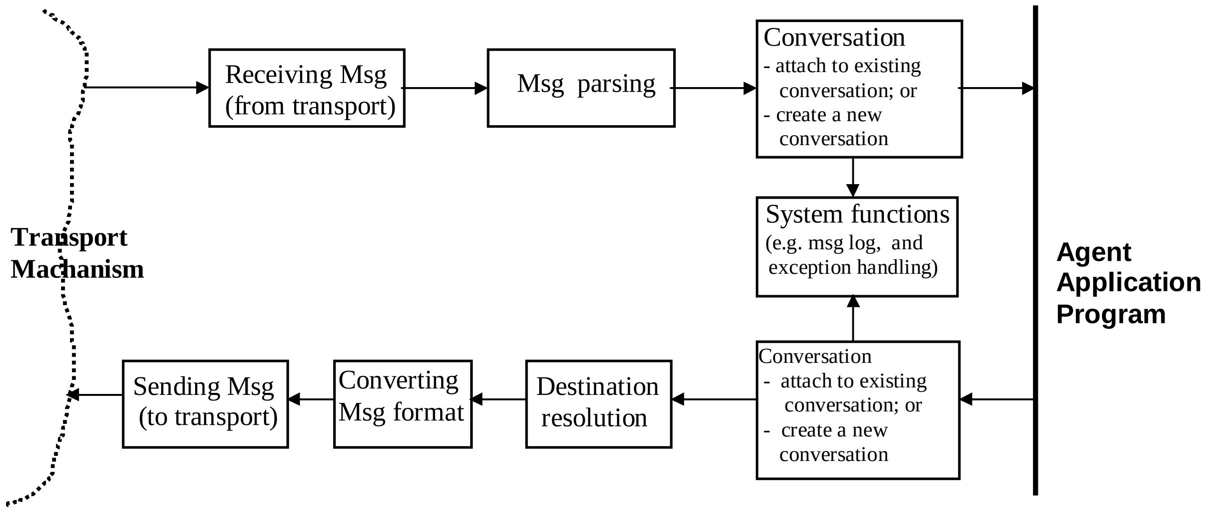


DFA state transition diagram for *subscribe* conversations.

3.2. Jackal architecture

To have a better understanding of Jackal, we shall follow the path of an incoming message and that of an outgoing, shown in Figure 2 below. When an incoming message arrives at the agent, it is picked up by the message-receiving module (a listener) and passed to the KQML message parser. The parser converts the message into a standardized internal format (Java object representation). Next, the message (in internal format) is passed to the conversation module for conversation resolution. The conversation module first determines whether the message belongs to an ongoing conversation (e.g., a *tell* message in reply to an *ask-one* previously sent out from this agent). This is done by matching the unique conversation id of the message (the in-reply-to field of the incoming message) with id's of the ongoing conversations (the reply-with field in the message that initiates the conversation). If a match is established, the message is then attached to that conversation. Otherwise, a new instance of an appropriate conversation and its DFA are created, and the message is attached to that new conversation. In either case, when a message is attached to a conversation, the corresponding DFA changes its state; the message, together with the required action (default or user specified function), is passed to the application program.

When the agent wants to send a message (either in response to a previous message or a new message to start a new conversation), the outgoing message is passed to the conversation module. Similarly to the case of an incoming message, the conversation resolution is conducted. The message is then passed to the lower layer where the destination address is resolved, the message is then converted into the format appropriate for the underlying transport protocol and sent out.



Receiving Msg (from transport)
Msg parsing
Conversation
- attach to existing conversation; or
- create a new conversation
System functions
(e.g. msg log, and exception handling)
Transport Machanism
Agent Application Program
Conversation
- attach to existing conversation; or
- create a new conversation
Sending Msg (to transport)
Converting Msg format
Destination resolution

Figure 2. Life of a KQML Message in Jackal

The diagram in Figure 3 below outlines the Jackal implementation. Several features distinguish our implementation from others. Jackal supports single, multiple and hierarchical ANS. It is designed in such as way that it can be easily extended to support multiple transport mechanisms in a single MAS. Also, to ensure that every message complies with the conversation policies across the board, the main components (*Message handler, Conversation arena,* and *Distributor*) treat incoming and outgoing message in the same way.

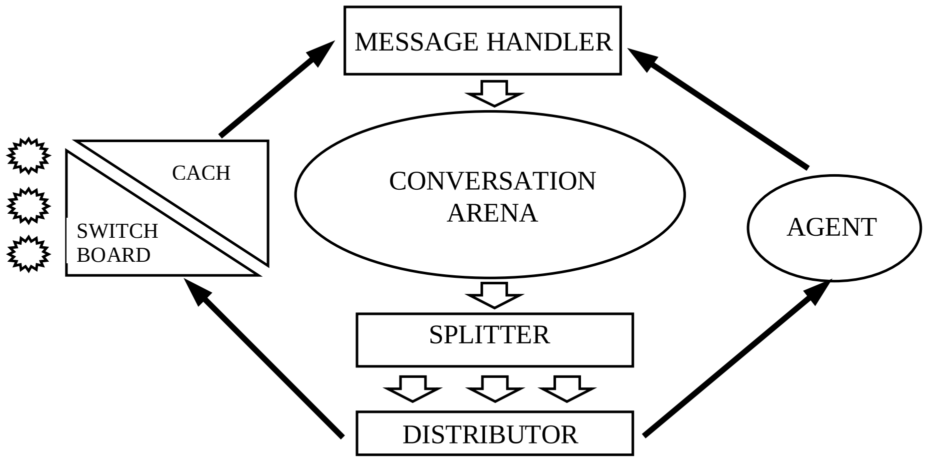


Figure 3. Jackal architecture

The *Message handler* handles conversation resolution for both incoming and outgoing messages based on matching of the reply-key parameter. DFA state transitions for conversations are performed in the *Conversation arena*. If a conversation policy is violated, an error message will be generated. The *Message splitter* duplicates messages for multiple destinations (e.g., broadcast or cc messages). The *Distributor* is the communication focal point for agent processes. It maintains two queues: a message queue where all unconsumed messages are stored; and a request queue where all unmet requests for messages are stored. Message requests are generated in accordance to the policies for ongoing conversations. When a new (incoming or outgoing) message arrives, the distributor will first check the request queue to see if there is a request for this message. If there is such as request, then the request is removed from the queue, and this message is consumed (either sent to the agent application program if the message is incoming, or sent to the switchboard if the message is outgoing). New requests are processed similarly. The *Switchboard* deals with the physical level of the communication, and performs the following functions. It translates the KQML messages between the internal format (Java objects) and the format required by the transport mechanism. It finds the physical addresses for outgoing messages with the help of the ANS and the agent's own address *Cache* module. It supports multiple transport mechanisms, and can switches from one to another according to the mechanism used by the message destination agent.

4. An Application Example

In this section, we demonstrate how the agent system supports intelligent enterprise integration through a simple business scenario involving some real manufacturing management application software systems.

4.1. The scenario

The scenario selected, called "*process rate change*", occurs when the process time of a given operation is reduced significantly from its normal value. When this type of event occurs, different actions need to be taken based on the type of operation and the severity of the rate reduction, Some of the actions may be taken automatically according to the given business rules, others may involve human decisions. Some actions may be as simple as recording the event in the logging file, others may be as complicated and expensive as requesting a re-scheduling based on the changed operation rate. The process rate change scenario is depicted in Figure 4 below. Note that two real application programs, namely the FactoryOp (a MES by IBM) and MOOPI (a Finite Scheduler by Berclain) are used in this scenario.

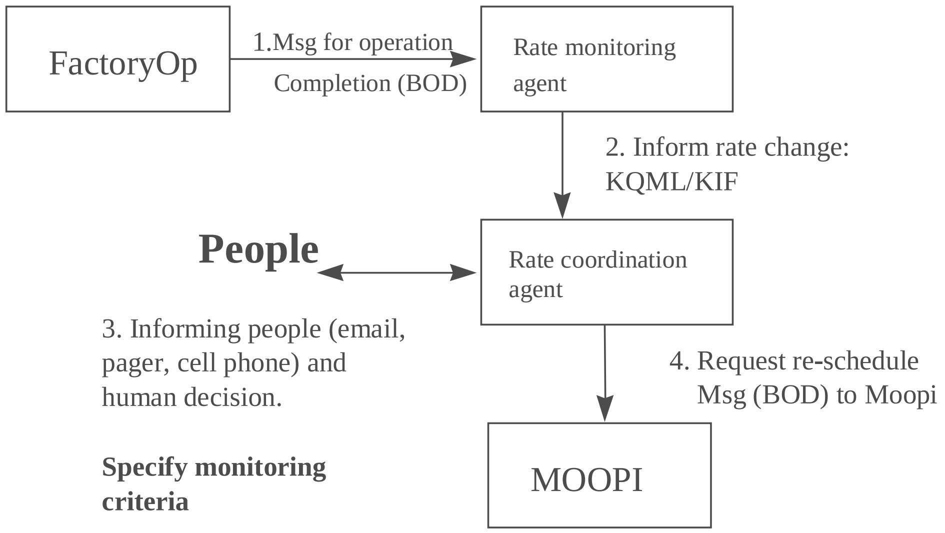

FactoryOp
1.Msg for operation Completion (BOD)
Rate monitoring agent
2. Inform rate change: KQML/KIF
People
Rate coordination agent
3. Informing people (email, pager, cell phone) and human decision.
4. Request re-schedule Msg (BOD) to Moopi
Specify monitoring criteria
MOOPI

Figure 4. The "process rate change" scenario

4.2. The agents

To support managing this scenario, we need mechanisms for the following activities.

- Collect information concerning operation completion originated from MES.
- Compute and constantly update the process rate from the collected information.
- Detect and notify the appropriate parties if the current rate change constitutes a significant reduction.
- Carry out appropriate actions to handle the rate change.

A collection of agents is assembled to support the chosen scenario. All of these agents speak KQML, and are supported by Jackal. Besides the three service agents ANS, BA, and GA, the multi-agent system also includes the following special agents.

- The *Process Rate Agent* (PRA) is both a mining agent and a monitoring agent for shop-floor activities. As a mining agent, PRA requests and receives the messages containing transaction data of operation completion from GA. The data is originated from FactoryOp in the BOD Format, and is converted into KIF format by GA. PRA aggregates the continuing stream of operation completion data and computes the current mean and standard deviation of the processing time for each operation. It also makes the aggregated data available for other agents to access. As a monitoring agent, PRA receives from other agents the monitoring criteria for disturbance events concerning processing rates and notifies the appropriate agents when such events occur.
- The *Scenario Coordination Agent* (SCA) sets the rate monitoring criterion, receives the notification for the rate change, and decides, in consultation with human decision-makers, appropriate action(s) to take for the changed rate. One of the actions would be to request MOOPI to re-schedule if it is determined that the rate change makes the existing schedule impossible to meet. This request is sent from SCA as a KQML message to GA where it is converted into the BOD format.
- The *Directory Assistance Agent* (DA) is an auxiliary agent responsible for finding appropriate persons for SCA when the latter is in need to consult human decision-makers. It also finds the proper mode of communication to that person.
- The *Authentication Assistance Agent* (AA) is another auxiliary agent used by SCA. It is responsible for conducting authentication checks to see if a person in interaction with SCA has proper authority to make certain decision concerning the scenario.

4.3. The predicates

Three KIF predicates of multiple arguments are defined for processing the process rate change scenario. Their names are OP-COMPLETE, RATE, and RATE-CHANGE.

Predicate OP-COMPLETE contains all relevant information concerning a completed operation such as the machine-id, product-id, operation-id, starting and finishing time of the operation. Each instance of this predicate corresponds to a BOD originating from FactoryOp, and GA is responsible for converting the BOD to this predicate.

Predicate RATE contains all relevant information concerning the current rate of a particular operation at a particular machine with a particular product. The operation rate is represented by its mean and standard deviation. Instances of Rate predicate are computed and constantly updated by PRA based on a stream of instances of predicate OP-COMPLETE obtained from GA.

Predicate RATE-CHANGE contains all information needed to construct a BOD that tells MOOPI a significant rate change has occurred and a re-schedule based on the new rate is called for. In particular, it contains the operation rate used to compute the current schedule and the new rate. It is the responsibility of the rate SCA to compose an instance of the RATE-PREDICATE and sends it to GA when it deems necessary to request MOOPI for a re-schedule, based on the process rate change notification from PRA and consultation with human decision makers.

Additional predicates and more complicated KIF expressions are needed when dealing with more complicated scenarios.

4.4. Agent collaboration and the message flow in the agent system

Figure 5 below outlines how agents are cooperating with one another to resolve the rate change scenario, and sketches the message flow in the agent system. For clarity, ANS and its connections to other agents are not shown in the figure. The message flow employed to establish connections between SCA and DA and AA (brokered by BA) is also not shown.

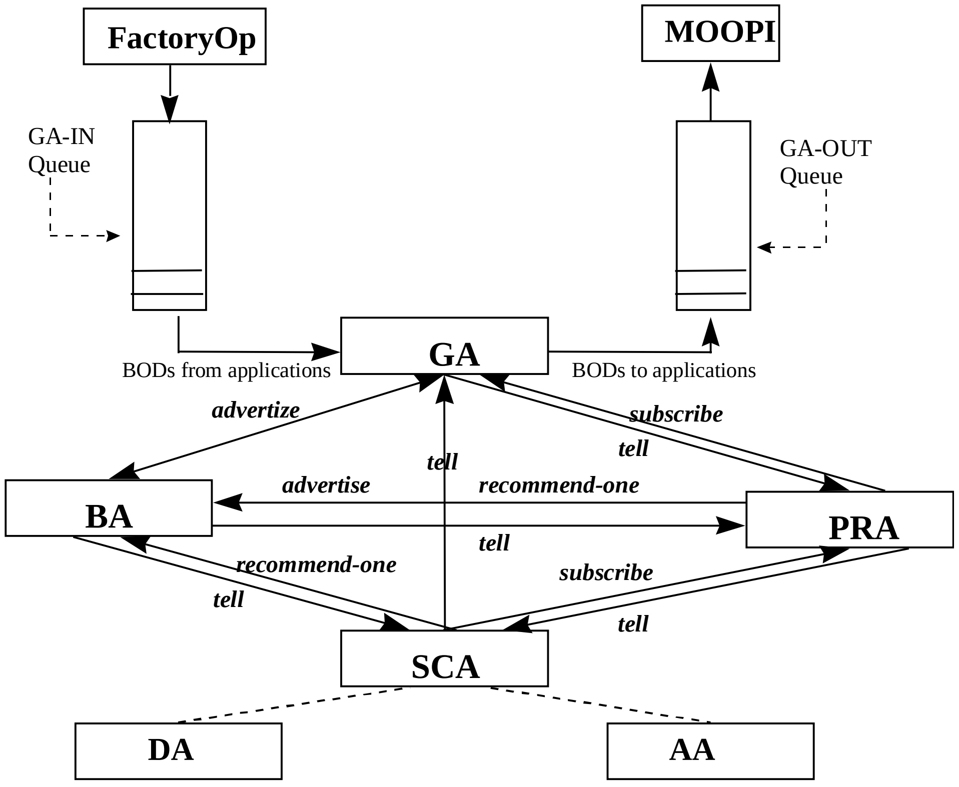


Figure 5. The agent system for "process rate change" scenario

Each of these agents needs information from others to perform its designated tasks. Each of them may also have information others need. There is no pre-determined stationery connection between agents. The broker agent (BA) plays a crucial role in dynamically establishing communication channel for agents' information exchange.

Advertising to BA.

GA advertises that it can provide OP-COMPLETE predicate. It also advertises to be able to accept RATE-CHANGE predicate and forward it to MOOPI as BOD messages. PRA advertises that it has current process rates available for some operations in the form of RATE predicate. The following is an example of *advertise* message from GA to BA.

```
(advertise
    :sender       GA
    :receiver     BA
    :reply-with   null8599132710561
    :content      (subscribe :content (ask-one :content (OP-COMPLETE  ?x1 … ?xn))))
```

Requesting recommendation from BA.

PRA asks BA to recommend an agent that can provide OP-COMPLETE predicate, and will receive the recommendation of GA in a responding *tell* message. Similarly, SCA asks BA to recommend an agent that can provide RATE predicate and receives PRA in response. It also asks BA to recommend an agent that can accept RATE-CHANGE predicate and receives GA in response. The following is an example of *recommend-one* message from PRA.

```
(recommend-one
    :sender       pra
    :receiver     ba
    :reply-with   null222222222
    :content      (subscribe :content (ask-one :content (OP-COMPLETE ? ? … ? ?))))
```

In response, BA sends the following *tell* message to PRA.

```
(tell
    :sender       ba
    :receiver     pra
    :in-reply-to  null222222222
    :reply-with   null333333333
    :content      (ga))
```

Upon the recommendation from BA, an agent can then obtain the needed information by sending *ask* or *subscribe* messages to the recommended agent.

Monitoring/notification

When SCA knows from BA that PRA has advertised to be able to provide the current rate for certain operation, it may send PRA the following *subscribe* message.

```
(subscribe
    :sender       sca
    :receiver     pra
    :reply-with   null444444444
    :language     KQML
    :content      (ask-one
                      :language    KIF
                      :content     (and (RATE  … ?mean …) (< ?mean 50))))
```

With this message, SCA tells PRA that it is interested in receiving new instances of RATE predicate whenever the mean value of the new rate is less than 50. This effectively turns PRA to a process rate monitor with the mean < 50 as the monitor criterion. Whenever the newly updated rate satisfies this criterion, PRA immediately notifies SCA by sending it a *tell* message with the new rate's mean and standard deviation.

5. Conclusion

It this paper we presented a multi-agent system that is capable of supporting intelligent integration of manufacturing planning and execution. With this approach, a set of software agents with specialized expertise can be quickly assembled to help gathering relevant information and knowledge and to cooperate with each other, and with other management systems and human managers and analysts to arrive at timely decisions in dealing with various enterprise scenarios. This system has been tested successfully with a real manufacturing scenario involving real legacy MES and scheduler.

The work presented here only represents the first step of our effort toward agent-based enterprise integration for manufacturing planning and execution. Further research and experiments are needed to extend the current work and to address its shortcomings. Although KQML does not impose much constraint and requirements on the internal structure of agents, it may be beneficial to have a common framework for the agent's internal structure within a single agent system. We are currently considering a light-weight blackboard architecture for such a framework which, among other advantages, may provide flexibility for agent construction, agent component re-usability and plug-and-play. Another research direction under active consideration is to increase the functionality of the broker agent and make it more intelligent. The BA in our current implementation can only conduct brokering activities at the level of predicates. With the help of a machine interpretable common ontology and an inference engine, more intelligent brokering can be developed to work with object hierarchies and to make intelligent choices. Work is also under way to identify more complex enterprise scenarios which require non-trivial interactions with more legacy systems and their solutions represent significant added values to the manufacturing production management.

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