Studies on Communication Strategies in Cooperative Search

檜崎, 修二

https://doi.org/10.11501/3111011

出版情報：九州大学, 1995, 博士（工学）, 論文博士
バージョン：
権利関係：

Chapter 4

Evaluation and Discussion

In this chapter, we evaluate two strategies through simulations using Traveling Salesman Problem (TSP) as an example of a search problem. Under varying communication costs, both strategies show good performances. We also discuss the adaptability and extentionality of our strategies.

4.1 Traveling Salesman Problem as a Cooperative Search

We mueasure the quality of the strategies through simulations using the *Traveling Salesman Problem* (TSP). TSP was defined by A. J. Hoffman and P. Wolfe in p. 2 of [LLARKS85] as:

> The TSP for a graph with specified edge lengths is the problem of finding a Hamiltonian cycle of shortest length.

A Hamiltonian cycle is a cycle that contains all the vertices of the graph exactly once. TSP is a well-known NP-hard problem.

We implemented the range control strategies on both flat spatial structures and hierarchical ones, the frequency control strategy and a fixed strategy for comparison. And search algorithm we used is the *branch-and-bound* method on search agents that run in parallel. They exchange the cost of the current best path as a threshold value. Since the quality of the threshold increases monotonously, merging some pieces of information (threshold) means only selecting the best one among them. It relieves the expectation cost. The pseudo-coded algorithm is the following:

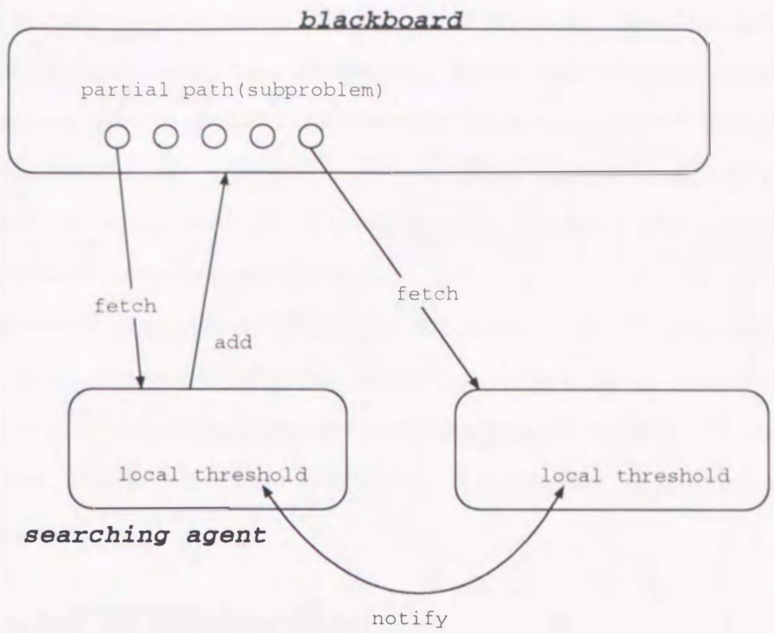


Figure 4.1: structure of TSP system

```
put initial state in global bag
do in parallel {
  while ( global bag is not empty ) {
    pick up a node from global bag that is better than local threshold
    expand it and return new nodes to global bag
    if ( a new node is better than threshold )
      update local threshold and multicast it
  }
  update history
}
report the best path
```

Italic statements in the code is for cooperation.

In this simulation, the number of cities is 10 and the length of histories is 10. The system consists of 100 agents. In this case, the threshold updates over 200 times. After each expanding node, the difference between the value of current threshold and the one before the expansion is stored in the history memory of an agent. Since the history holds the revision of threshold, we can calculate the expected values of threshold that other agents get most recently. Thus a Monte Carlo simulation on the history gives the agent the expected best value among n

agents. At every step, agents select a communication structure. Since the simulator models asynchronous network, the range control strategy on hierarchical structures requires some steps of communication in order to change the cluster size. If the probability of information updates is uniformed distribution, the expectation formula 3.6 in the previous chapter can be used instead of the Monte Carlo method. We will describe the result of a comparison between formula 3.6 and the Monte Carlo simulation.

Here we show some properties of TSP. Figure 4.2 shows the distribution of answers in eight city's TSP. Its range is large and the average is two time worse than the optimal answer. Figure 4.3 shows a trace of the renewal of threshold in solving by a single agent. The value of renewal is almost random. We can expect the assumption that renewals are uniformly distributed is not bad estimation.

4.2 Results of Simulations

Our simulator was build on Common Lisp. Exactly speaking, we use CLOS/MOP's features. Each agent is implemented as an instance of a class. Its details will be described in the next chapter. Each agent runs in round robin. Dispatch granularity is the same as a main method. Communications in a stage occur simultaneously at the end of the stage. When an agent resumes, it checks its queue for received packets. Thus all messages are received the next stage of the sending stage. Every range control strategys can change the communication range (cluster size) in ± 2 at each step. They evaluate the utility of communication using the five points: not change, increment by one or two, and decrement by one or two. The strategy selects best one out of them. Though this process can not select the best size at once, this implementation avoids oscillation. Figure 4.4 shows a sample of the changes of the cluster size. We fixed the optimal size to 10. But at the first step, all cluster sizes are one: each agent belongs to a cluster. They must change their cluster sizes to the optimal ones. Though some clusters achieve the optimal size quickly, in general, our structure-changing protocol that is mentioned at the previous chpater requires a long time for this transition. We expect the changes of the optimal size in real problem solving is small in a short period.

Through all experiments, we ignore the cost of getting subproblems from the global bag.

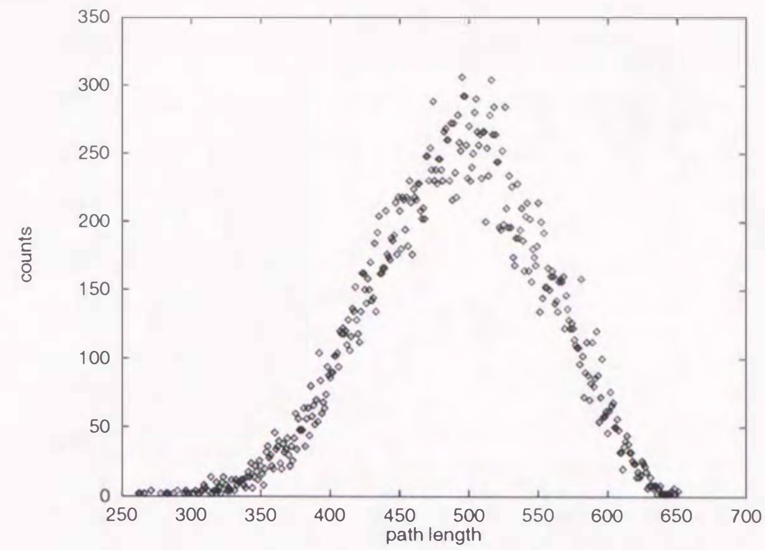


Figure 4.2: distribution of all distances in a TSP

The number of cities is 8. Thus the number of possible solutions is $8! = 40320$.

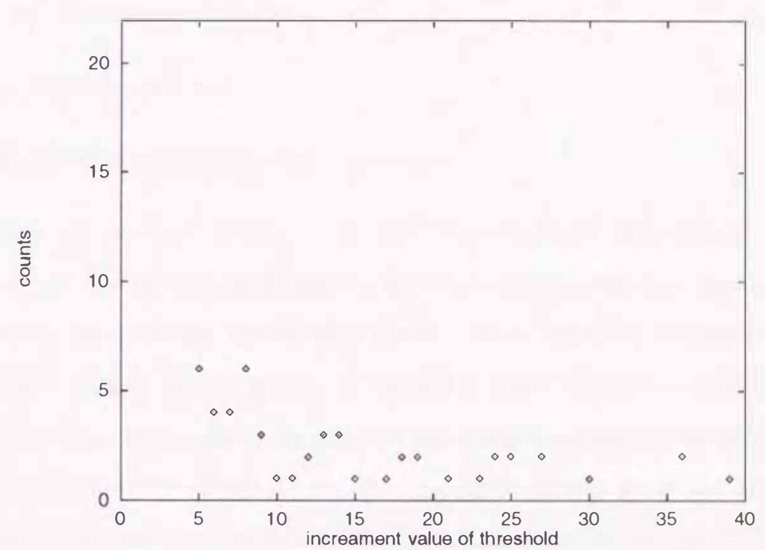


Figure 4.3: distribution of the renewal values

4.2.1 spatial connectivity control strategy

First, we examine the frequency control strategy. As we described in the previous chapter, there are three substrategies:

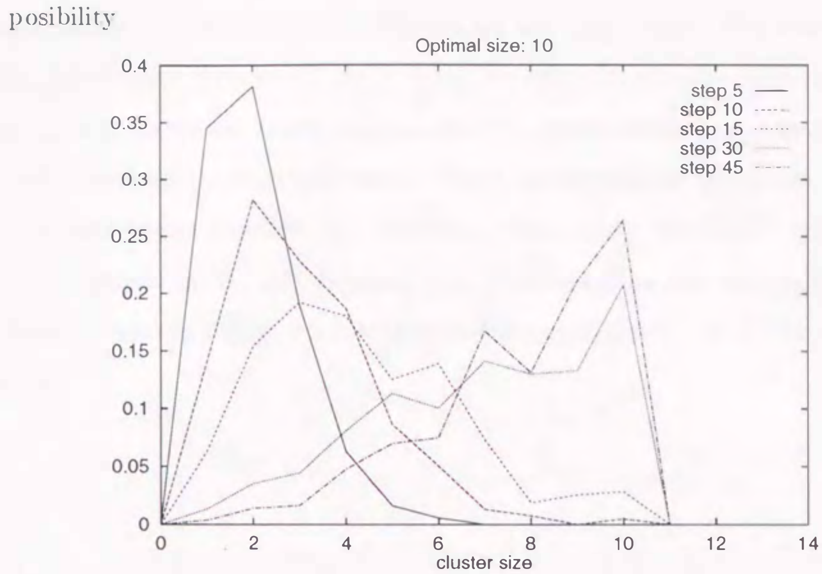


Figure 4.4: changes of clusters' size

- fixed in flat structures
- fixed in clustered structures
- changing spatial structures during execution

Here we examine all three strategies. The first two strategies only change the number of receivers. Last one has a threshold that is the trigger to change the spatial structure. In this examinations, we give the threshold a priori. If an expected communication range is smaller than the threshold, agents apt to use flat structures. Otherwise, agents attempt to use cluster structures. Exactly speaking, in order to avoid a perturbation between two structures, our implementation use $\alpha \times$ threshold for the trigger to transit from flat to clustered, and $1/\alpha \times$ threshold for the reverse transition. We use 4.0 as the threshold and 0.81 as α.

Results are shown in Figure 4.5,4.8, and 4.9. They show that the strategies achieve good performance against affected communication costs. The data are averages of $10 \sim 100$ experiments.

Figure ?? and 4.7 compare the two estimation methods. Formula 3.6 could achieve as good performances as the Monte Carlo method in TSP.

The communication cost function in Ffigure 4.5 are simple ones. The ones used in Figure 4.8 non linear functions. This non-linearity is introduced to imitate the congestion on network. In Figure 4.9 that shows the traces of the size of the range with the communication cost at Figure 4.8 (a), the solid line shows the range control strategy on flat structures, the dashed line shows the optimal size on hierarchical structures, and the dotted line is the real size of clusters on hierarchical structures. Strictly speaking, the communication cost used in Figure 4.9 (b) is different from the one in Figure 4.9 (a). The cost function hardly affects the tendency of the range change.

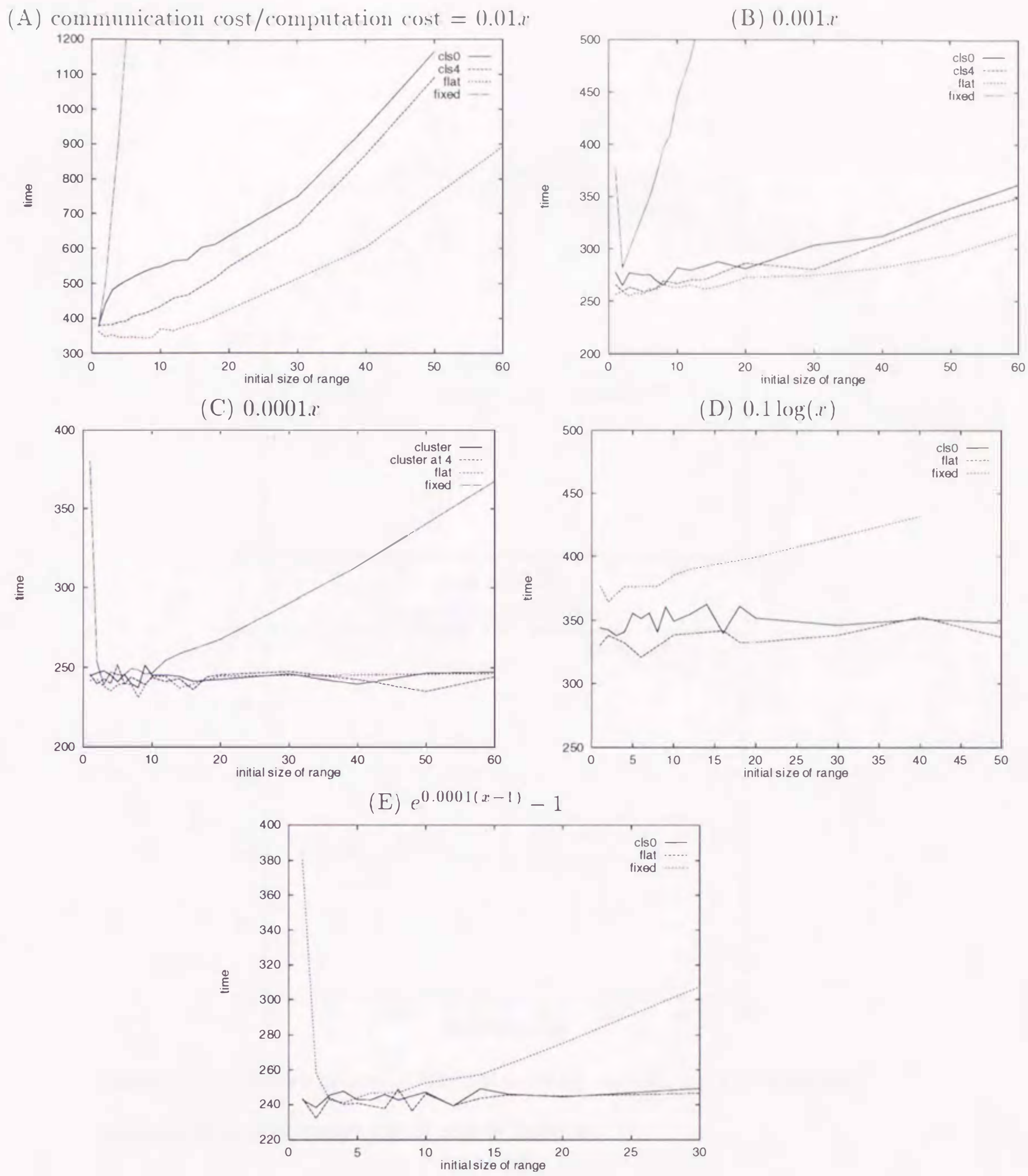


Figure 4.5: results of spatial strategies(1)

The average time of a single agent system is 21501. Thus the region under 215 means superlinear.

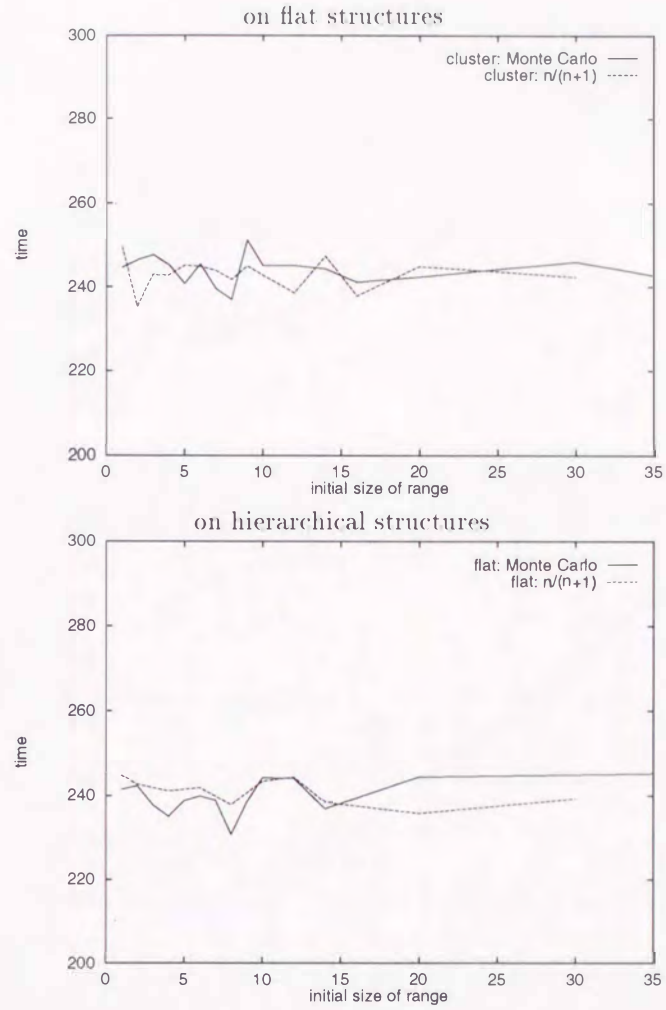


Figure 4.6: difference of Monte Carlo simulation and $n/(n+1)$ estimation

communication cost/computation cost is $0.0001x$

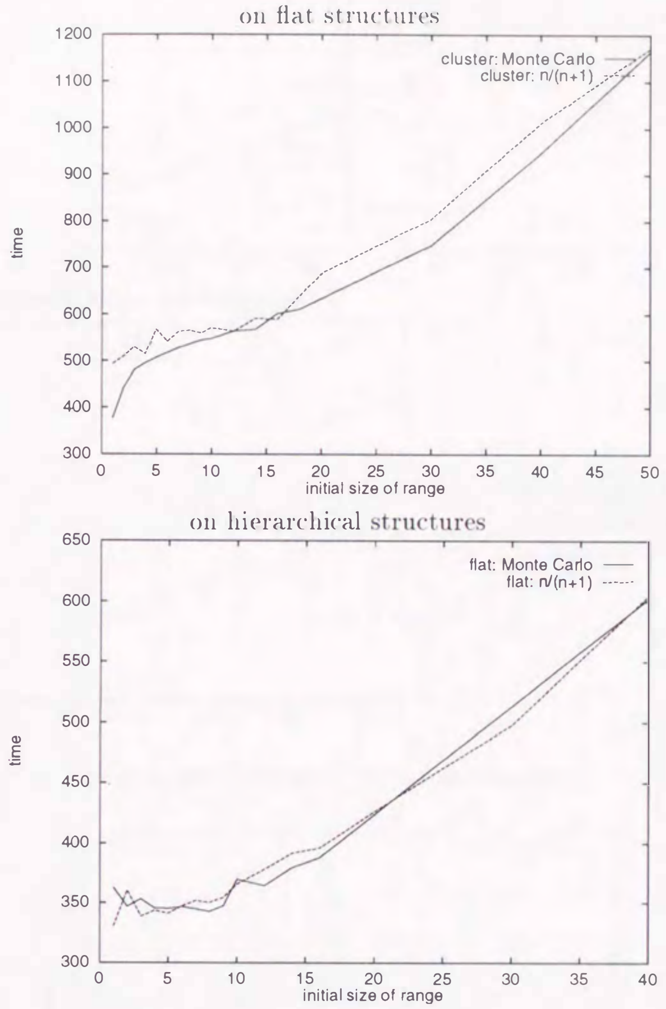


Figure 4.7: difference of Monte Carlo simulation and $n/(n+1)$ estimation(2)

communication cost/computation cost is $0.01x$

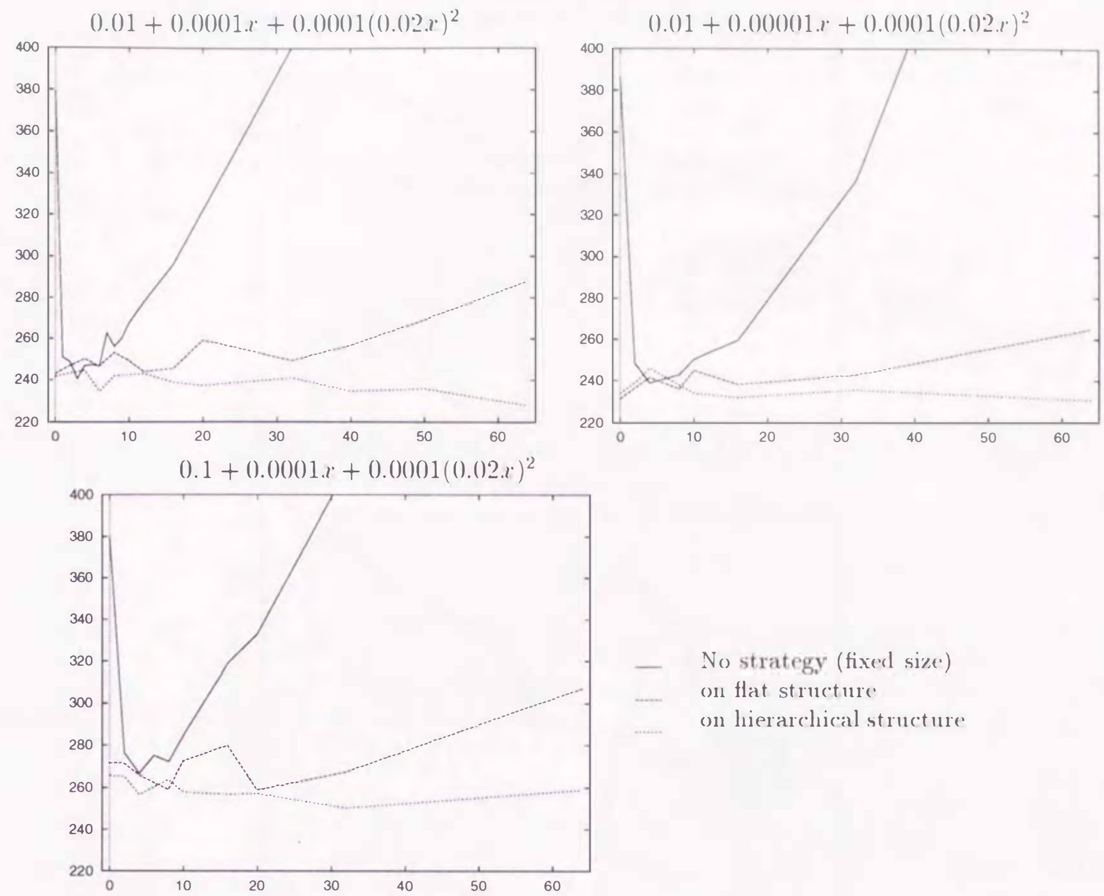
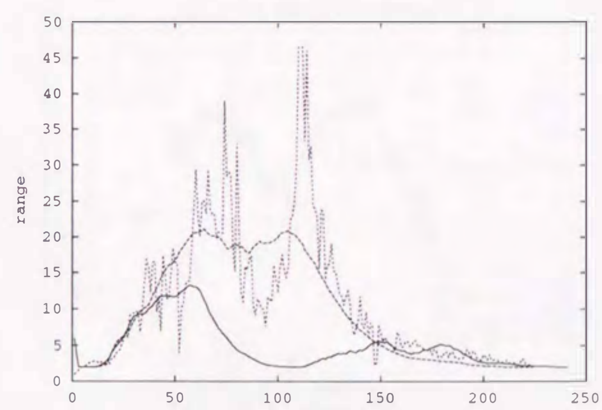


Figure 4.8: results of spatial strategies(2)



changes of the communication range

Figure 4.9: results of spatial strategies(3)

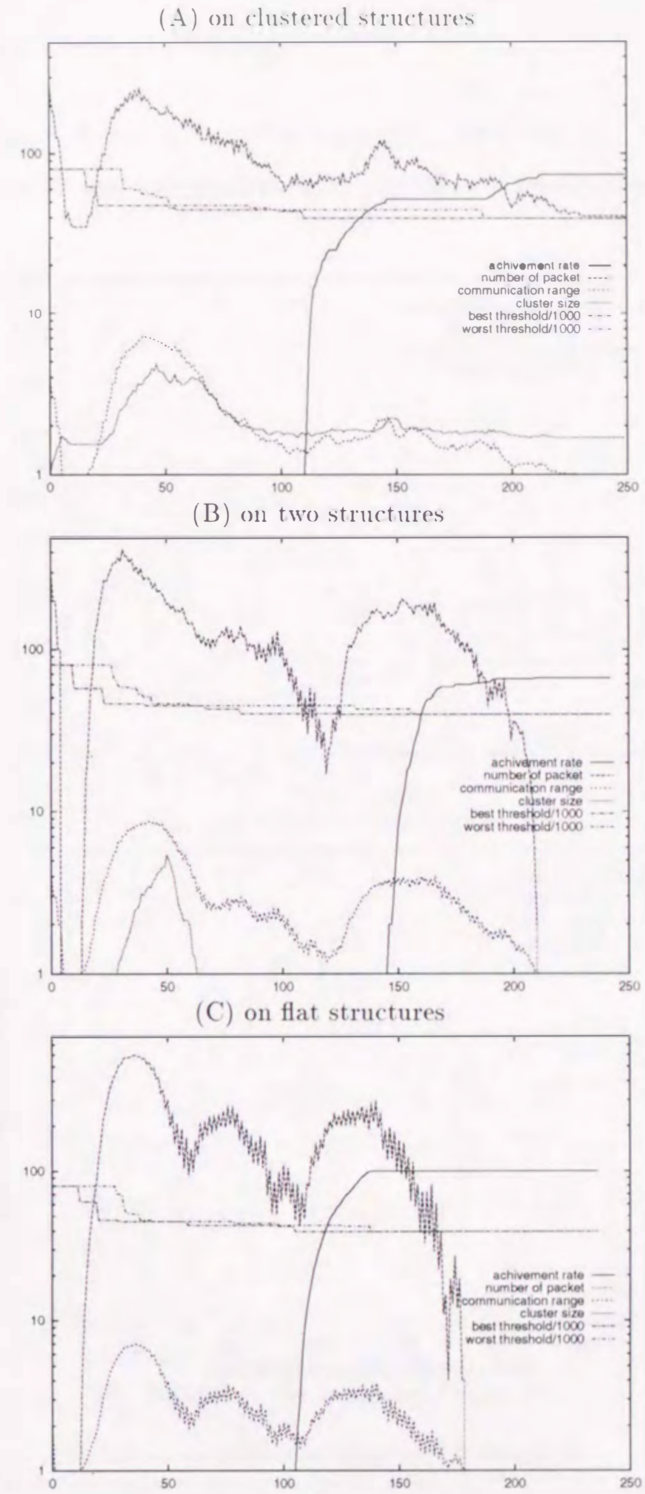


Figure 4.10: traces of the size of the range

4.2.2 frequency control strategy

The second category of strategies is the frequency control strategy. Our current implementation is based on the manager-worker model and different from a structure for the range

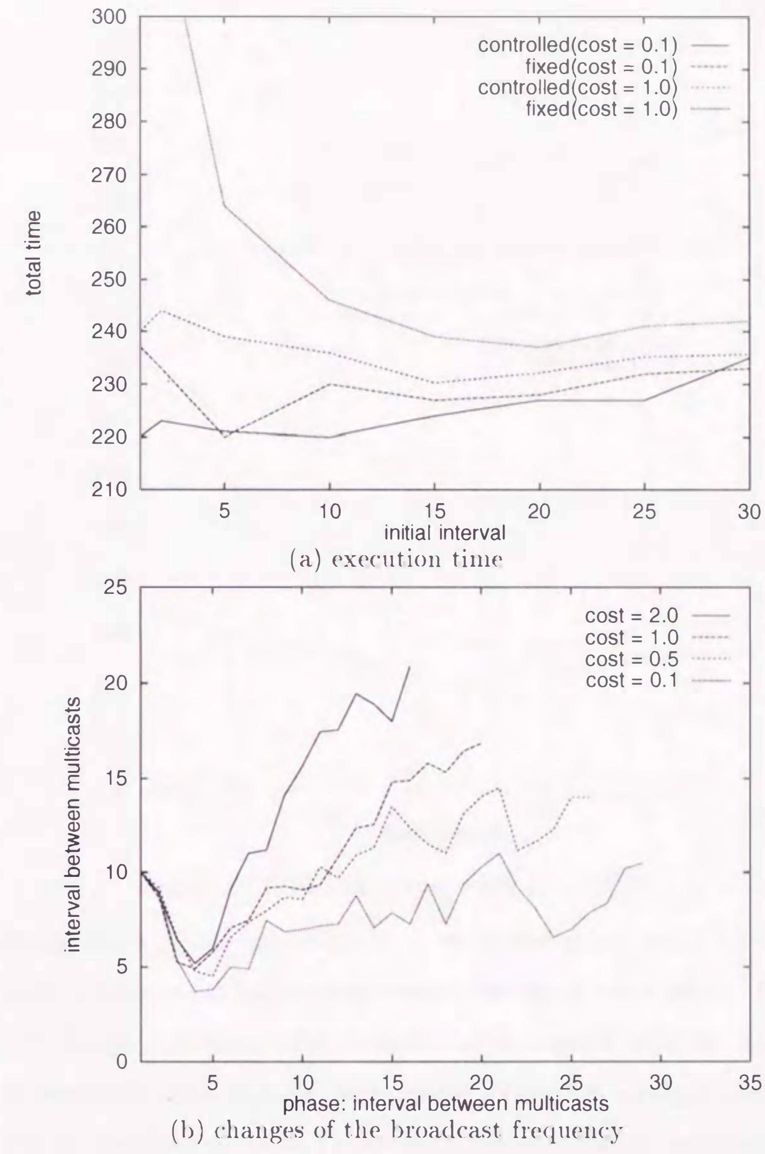


Figure 4.11: results of frequency strategy(1)
The cost of communication is shown as the ratio compared with the computation cost. 'Phase' is the local computation step between two broadcasts.

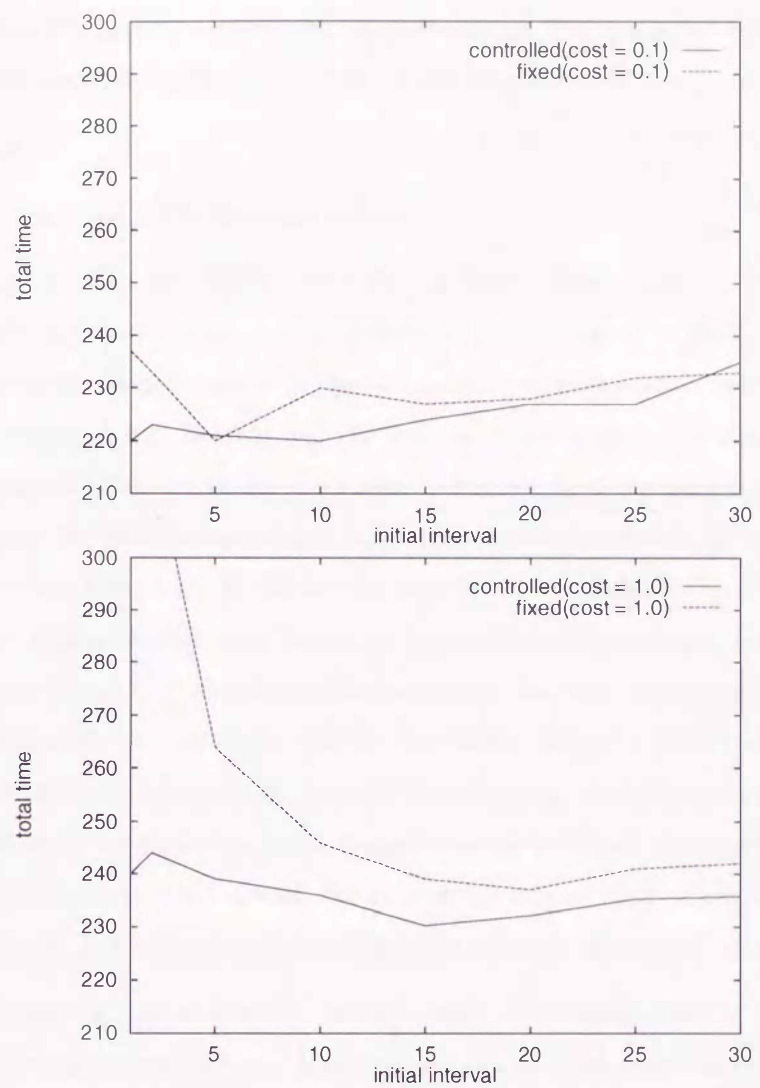


Figure 4.12: results of frequency strategy(2)

control strategy in which agents are identical in the initial state. Only one manager determines the frequency of mulitcast based on the result of its local computation. If it decides that it is a time to exchange local knowledge, it multicasts a request for exchanging information. Receivers send back their knowledge to the manager. Then the manager multicasts the best knowledge of the received pieces. In this three-phase communication, every agent should stop local computation.

Most parameters for experiments for the frequency control strategy is the same as the ones in the experiments for spatial connectivity control strategy. The number of agents is 100: one manager and 99 workers. Figure 4.11, 4.12 is the results.

4.2.3 results

The properties we found are summarized below:

1. Changing the range and the frequency during the execution is useful. The initial range hardly affects the performance in both flat and hierarchical structures. As Figure 4.10 shows, there are three stages from the view of the size of ranges on both structures. In the first stage (at $0 \sim 20$ step) and the last stage (over about 150 step) the communication range is relatively small. This result is derived from the nature of the searching process. At the initial stage, for no agent finds a new threshold, the strategy reduces the communication range. In the middle stage (at $20 \sim 150$ step) where the distribution of agents' information becomes large, the range becomes very large. In particular, the strategy on hierarchical structures changes sharply, because an information collector of a cluster controls the size of the cluster. The best answer was often found at $80 \sim 150$ step. At the last stage after finding and broadcasting the best answer, updating the threshold never occurs and no more communication is needed. In conclusion, the more frequently information is renewed, the more frequently or more widely identical agents communicate. But excessively frequent updates decrease the number of communication.

2. In the frequency control strategy, the frequency of communication is affected by the communication (broadcast) cost. Similarly, the size of communication range decreases if its cost is high where the utility of communication becomes low.

3. There is no clear difference between flat structures and hierarchical structures. The reason is the peak size of ranges is not so large in this simulation and changing cluster size requires some other communication on hierarchical strategies. This reduces the merit of hierarchical structures. However, experiments with other cost functions showed large communication costs make the difference clear. For example, in Figure 4.5 (A), (B) and (C), the difference becomes small in its order. Generally, the structure changing strategy is better than the strategy on cluster structures.

4. A communication range becomes larger after the difference between the best knowledge and the worst knowledge in time becomes large. A history has enough sensitivity. This result corresponds to the result that we mentioned in the previous chapter.

5. The best threshold spreads quickly when it is found. Sometimes search terminates before every agent knows it. But usually most agents know it. Since, compared to flat structures, cluster structures apt to make closed groups in each clusters, expansion speed tends to be slower than the one on flat structures.

The properties described above are held in other communication cost functions from $O(\log(n))$ to $O(\exp(n))$. They hardly depend on a cost function if it increases monotonously. In conclusion, programmers need not care about the communication topology by using the strategies.

4.3 Discussion

4.3.1 applicability of the strategies

In this section, we discuss the applicability of these strategies to other fields and ways of implementing these strategies. Related works are also described.

another search algorithms

First, we think more about the branch-and-bound method. As we described, our implementation ignores the communication cost for gathering subproblems into a blackboard. We justify this assumption as we can implement it as distributed memory easily. But if so, we should deal with the local starvation of the problem. Of course, any agent can multicast or send a request to neighbors when the local bag is empty. But agent must wait for its results. If we do not want to make agents idle, agents sent a request of subproblems to other agents before it becomes really idle. Thus we had better build a cooperative communication strategy to require subproblems. A local history about the consumption rate will be a help. Then we can use our strategy, where it control the flow of subproblems instead of a threshold. Furthermore, by using a history of requests from other agents, it would behave more cooperatively.

Second topic is on A* search. The current shortest path as a threshold in TSP is a kind of information that is acquired during execution. The search algorithm used here does not use any estimation heuristics. In a general case, we can use an estimated value as the measure for modeling execution status. Considering A* search[Pea84], the quality of a node (subproblem) is measured by an evaluation function. Thus we can use the strategies for exchanging subproblems with the relations in Table 4.1.

Another cooperative searching method is bidirectional search [Poh71, Ish93b]. It is search from an initial state and a goal state simultaneously. Two search processes look for a path that they can meet. Locations of each agent in the search space will help for cooperation. Thus by giving a heuristic function like the proceeding rate, two agents behave in a cooperative manner; for example, agent require less computational time when it has not proceeded. A history will provide a basis for cooperation. Here, the cooperative strategy is not for communication. It changes an agent's behavior itself. But if the communication cost is very high, the communication strategy that can forecast other agents' states will be useful again.

out of search problem

Though we model only cooperative search problem, the connectivity changing strategies are applicable to a lot of areas. First we concern with the *contract net protocol* [DS88]. Contract net protocol is a method for distributing subproblems to appropriate agents. Each assignment takes three phase communication among agents: issuing a task announcement, submitting a bid,and making an award. A merit of this method is fairness of the result. These message are broadcasted. But with a history of replies, agents omit overspreding of messages. Agents use multicast instead of broadcast.

shared object management Second example is shared object management. Exchanging threhsold can be thought of as algorithms for managing the consistency of threshold that

Table 4.1: comparison of search algorithms

application	branch-and-bound	A* search
measure	update rate of threshold	update rate of estimated value
exchanged data	threshold	good unexpanded subproblem

is shared *weakly* among agents. In addition, the idea of using a local history as a model of an environment can manage shared objects with strong consistency. Usually, strongly consistent objects are used much more than weak consistent objects on distributed systems. Thus the programmers' burden of keeping coherency effectively will be relieved in a number of application areas.

In this case, the measure of execution is the ratio of local access and remote access. Values Exchanged among processors are shared objects themselves. If the current cost for remote access is higher than the expected cost for managing coherency, a shared object should be duplicated and distributed. On the other hand, if it is low, the copies should be merged to reduce the cost in writing. If agents (copies of a shared object) know the access ratio sufficiently with the access history, the strategies would work well.

4.3.2 dealing with heterogeneity

Our approaches assumes the homogeneity of agents. However, the history-based expectation mechanism could apply to not only homogeneous environments but also heterogeneous ones. The history of the revision of information at other agents in current implementations is not separated from its own history. Agents exchange the information with each other and update their histories with the received information. But in heterogeneous network, this dispersion becomes an important problem. An implementation and the evaluation of strategies based on separated histories are of a future plan. Such an implementation will also work on heterogeneous agents.

Another important heterogeneity is in decision making: diversity of actions of agents. If heuristics can find only the most promised search direction , the best path in time does not always lead to a way to the best answer. Thus for reducing the risk, diversity of search directions in some degrees is required. Lesser called such a search strategy that includes this diversity control as cooperative control [Les91]. We think temporal diversity of the selection of the next problems can be acquired from probabilistic way based on the local history, that makes an appropriate distribution of all agents in the system in a search space. But further study is required for this direction.

Last heterogeneity is aboout agents goals. Since we focus on DPS in which the goal is shared among all agents, situation like Prisoner's dilemma [Axe84] do not take place. But a kind of fluctuation or oscillation of decision making may take place. This problem is discussed in [KHH89]. Since our methods, however, use histories, we do not think drastic loss of the performance happens that is reported [KHH89].

Finally we summarize the limitations of the proposed scheme again:

1. Communication costs must be known before execution. It would be difficult on a system that has a hierarchical topology or a large-scale open system.

2. The strategies assume homogeneity of agents. But we gave some posible solutions to it above.

4.4 Summary

- Through simulations of TSP, we have evaluated the quality of our strategies. They showed better results than fixed communication systems for a wide range of communication costs.

- A history is a good model of execution status. There is no clear difference between the monte Carlo simulation and formula 3.6. They estimate the probability of information update well in the range control strategy.

- We discussed problems to apply our strategies to other search algorithms or other application domains. By proposing extension plans, we claimed that many of them will be solved.

- We also discussed some assumptions to use our strategies; the heterogeneity of agents and knowledge on cost functions.

Chapter 5

Separate Description of Communication Strategies

5.1 Communication Strategies as Metalevel Computation

Our communication strategies change the behavior of an agent by using a history that is a measure almost independent of a problem-level program. They are invoked when some changes in agent local status are happen. And after finishing their job, the control flow returns to the invoking point in the problem-level program. This flow reminds us a usual subroutine calls. But since when to invoke communication strategies is defined in the context of the strategies themselves, the interpreter can know it. This means programmers need not to write procedure calls down in their problem-level programs. In other words, communication strategies can be embedded into the semantics of reference and update of local variables in problem solving programs. It is a metalevel computation.

Thus we think deciding communication structures should be a kind of computational reflection [MN88]. This means communication strategies can be separated from problem-level programs and be a metalevel description of program solving agents.

This separation approach has two merits:

1. Programming is divided into two independent subtasks: building communication strategies and writing problem-solving codes. As a result, writing codes for communication

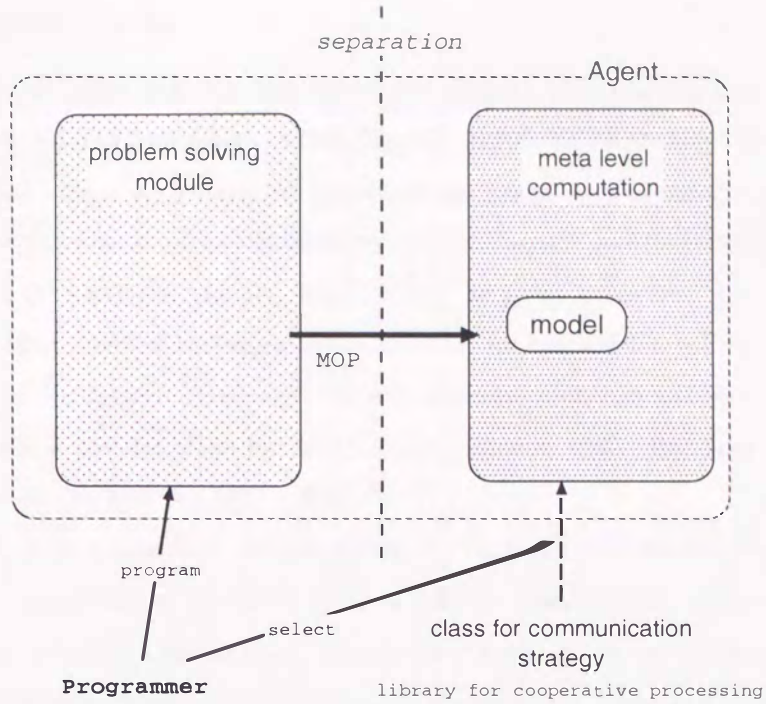


Figure 5.1: separate description

strategies can be omitted from problem-solving programmers' task. It also makes reusing the communication strategies easy, if there is a generalized protocol between agent and strategy. Communication strategies can be stored in a library. In Werner's words, we can distinguish "system programmers" and "application programmers" with this framework [Wer92]. As a result, communication strategies and application programs can be developed and tested independently.

2. Since the communication strategies are included in the semantics of a language, the strategies are invoked automatically when needed. For example, if a communication strategy is defined as metalevel computation of the assignment to a slot that holds information to exchange, every modification of the slot invokes the strategy. We can omit explicit invocation codes from problem-level program.

We made such a system on an object-oriented language. We explain this in the following sections.

5.1.1 related works

Relation between agent programming and object-oriented programming languages have been investigated by a lot of researchers [NT90] [Hew77, MIT90, YSTH87, MWY91, Gas92b, FB88, FC91, EPT94]. Most agent-oriented languages are based on first-order modal logic, since logic-based representation of specification can infer the agents' mental states like belief, desire and intention in a uniform manner, which select the agent behaviors. On the other hand, concurrent object-oriented languages with extensions for cooperation will be useful especially for DPS. Since our focas on language is how to separate problems and strategies, we do not intend to build a new language but build a programming style. But here we give a short summary on relation between DPS and OOPL.

[MWY91] is an approach to change behaviors in a group with metalevel computation. In this system a group has a metalevel. This is different from classical meta-object languages in which an object has a meta-object. Consistency in the group can be held easily. On the other hand, it requires frequent communication between nodes. Thus we do not think that this approach is rational in cooperative system on distributed systems.

Some concurrent reflective OOPLs like [FB88, FC91] have been used for DPS. For example, Ferver's Mering IV [FC91] is an example of object-oriented languages with meta-level computation for cooperative computation. His focus is providing high level communication primitives to programmers and not providing adaptive cooperative methods based on local computation. But there was no clear separation between cooperative strategy and user application program.

Some Object-oriented OS uses reflection for a method of load-balancing and process migration [OIT93, Yok93]. But the facility is embedded in OS and can not use the semantics of application program well. We think more strongly combination between strategy and application is required. Compiler's support is crucial.

5.2 Implementation on CLOS Meta-Object Protocol

Some object-oriented-programming languages have meta objects that represent behaviors of objects. In particular, CLOS (Common Lisp Object System) [S$^+$90, Kee89] has flexible interface to meta level programming, which is known as CLOS MOP (Meta-Object Protocol)

[KdRB91, Pae93b]. Thus we decided to build a DAI platform with the stategies on CLOS.

In the next section, we give a short description of CLOS/MOP.

5.2.1 meta-object protocol

A merit of object oriented programming languages (OOPL) is modularity of programming components or *objects*. A definition of a data structure and procedures for it are capsuled on a description block called a *class*. An *instance* of a class behaves as defined in its class. Some OOPLs can control behaviors of a class itself, that includes ways to make an instance, delete an instance, control method dispatch, inherit super classes and so on. These extensions are done by making class itself an instance of a class: a *metaclass*. In such languages, all classes have its metaclass. By letting all metaclasses accept same methods (called *protocols*), we can change the behaviors of instances of a class easily. We can select most appropriate metaclass for problem solving. Since such an extension to a user defined class is not modification of an existing system but an addition of new behaviors for a particular class, it is safe and easy for programmers. A group of researchers had proposed a protocol for the CLOS class structure. It became a standard known as *MetaObject Protocol* (MOP). CLOS MOP provides a way to change the behavior to access to a slot, update of it, make a new instance of the class and so on. For example, MOP has been used to emulate other inheritance/message-passing models (Dvorak's hybrid knowledge representation tool [DB93] and CLOVERS(`ftp://swiss-ftp.ai.mit.edu/archive/clovers/clovers-design-notes.text`)) and to build a persistent OOPL system (for example, PCLOS [Pae93b], AllegroStore(a commercial product based on Alegro Common Lisp), ITASCA ODBMS (ITASCS Systems Inc.). Lisp FAQ (`http://www.cs.cmu.edu:8001/Web/Groups/AI/html/faqs/lang/lisp/top.html`) summarizes more implementations).

Now the following is a summary of requirements for separate description of our communication strategies.

1. Change the behaviors of access/update of a particular slot of an agent. Our strategies store the history of renewal of a slot. The strategies that also include a procedure of update the history should be invoked whenever the slot is updated. Or some strategies

shold be invoked when the slot is accessed. This is a kind of extension of the semantics of the language.

2. The invocation should be transparent for programmers. Programmers who write problem-solving programs should never concern about communication strategies as much as possible. They do not want to call any procedures for a strategy explicitly.

3. Communication strategies can send and receive some sorts of messages. The messages should be invisible from problem-level programs. And a particular message dispatcher can be invoked when a message is received. This dispatcher must coexist with the dispatcher in problem-level program.

CLOS MOP provide features to meet these requirements. Thus we decide to implement the communication strategies with MOP. In the following sections, we explain our implementation.

5.2.2 class structure

Figure 5.2 shows the class hierarchy in CLOS. It also includes our new classes for describing communication strategies. In CLOS, every object is either one in CLOS class hierachy or one of a built-in type. all objects, even if they belong to a built-in data type, are subclasses of the object `T`[1]. T's superclass is `T` itself. top class of CLOS class hierachy is `standard-object`. It defines the primitive behaviors of all instances. Both of slots and methods themselves are subclasses of *standard-class*.

agent-class and agent-meta-class

First, we should define a new meta class *agent-meta-class* for a specifier of class behaviors. Its definition is as simple as listed below. Since slots holding information for communication strategies are stored in an instance of each strategy's class, agent-meta-class has no own slot. It is used only for slot instantiation. With it, as a base class of users' agent class, we define `agent-class`.

```
(defclass agent-meta-class ()
  ())
```

[1]In the Lisp dialects, `T` means true usually.

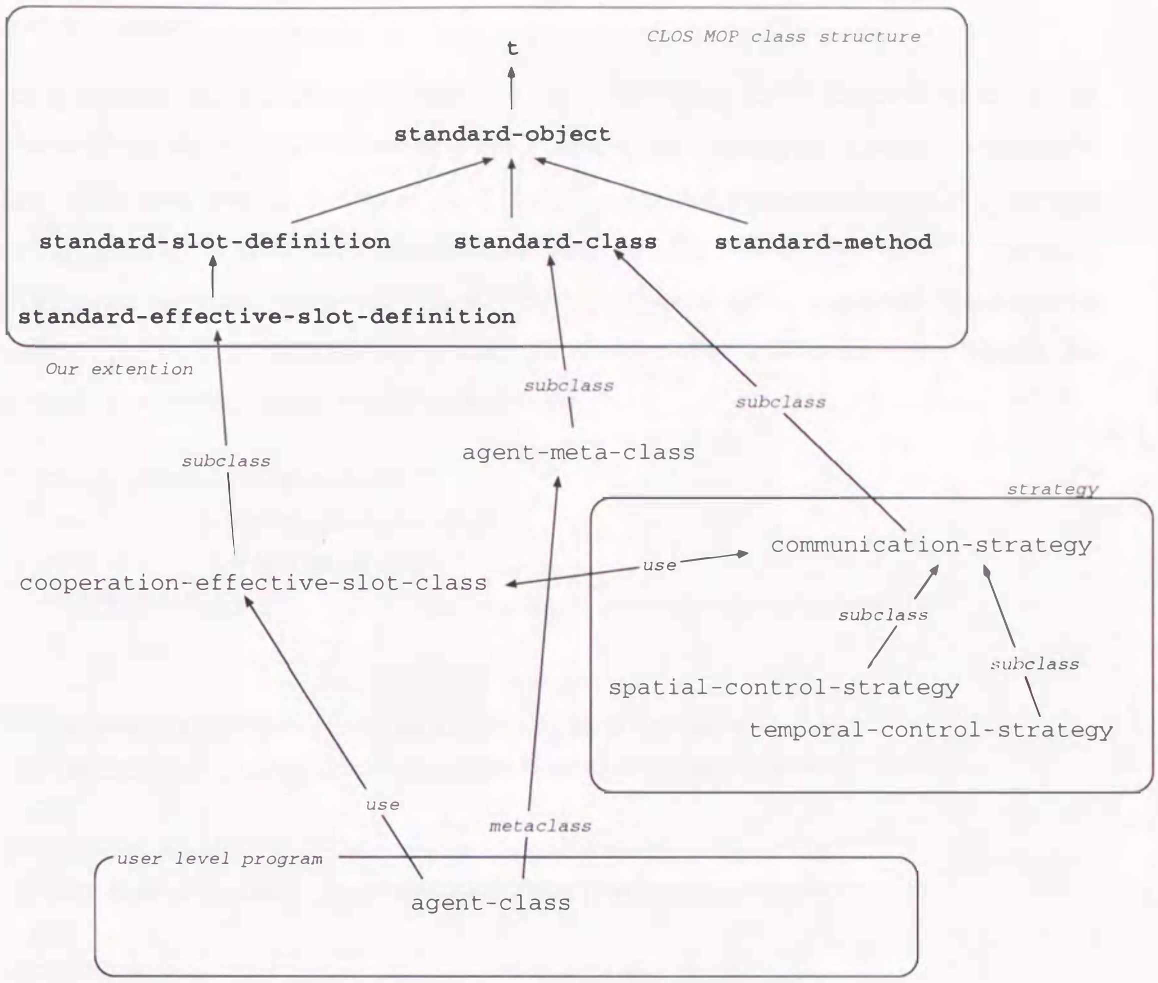


Figure 5.2: class hierarchy

(**defclass** agent-class () ; *super class is T.*
  ((receive-counter :accessor receive-counter :initform 0)
   (send-counter :accessor :send-counter :initform 0)
   (agent-id :accessor agent-id :initarg agent-id))
  (:metaclass agent-meta-class))

`agent-class` has two methods for inter-agent communication. They update the above two slots in agent-class.

(**defmethod** send ((self agent-class) (receiver/s object) ...)
(**defmethod** receive ((self agent-class) (message **t**)) ...)

slot structure

Our strategies use a history of slot renewal. It is a model of program execution. Since we assume that a history of the value renewal of a slot is used as the measure of program execution, the slot object must hold the history of itself. Thus it is rational to use an instance as a wrapper to hold them at the same time. All strategies have a common interface (protocol); a procedure in accessing the value, one in updating the value, and one in receiving messages from another agent. Thus we make each strategy a class. An abstract class: *communication-strategy* is one of their superclasses. It can be defined as follows.

```
(defclass communication-strategy ()
  ((value)        ; the wrapped value itself
   (model)        ; a history of value
   (communication-cost)        ; a function to estimate communication cost
   ))

(defgeneric ref-strategy ((class communication-strategy) instance slot)
(defmethod ref-strategy ((class communication-strategy) instance slot)
  nil)
(defgeneric set-strategy ((class communication-strategy) instance slot)
(defmethod set-strategy ((class communication-strategy) instance slot)
  nil)
(defgeneric dispatcher ((class communication-strategy) instance slot)
(defvar *out-of-local-computation-p* nil)
(defmethod dispatcher around ((class communication-strategy) instance slot)
   (let ((*out-of-local-computation-p* t))
     (call-next-method)))
```

Note that method `ref-strategy` is required to update the history of local computation that is stored in `model` slot. `*out-of-local-computation-p*` is a flag variable that is used to distinguish the value from an another agent from one found locally.

specify metaclass-designator

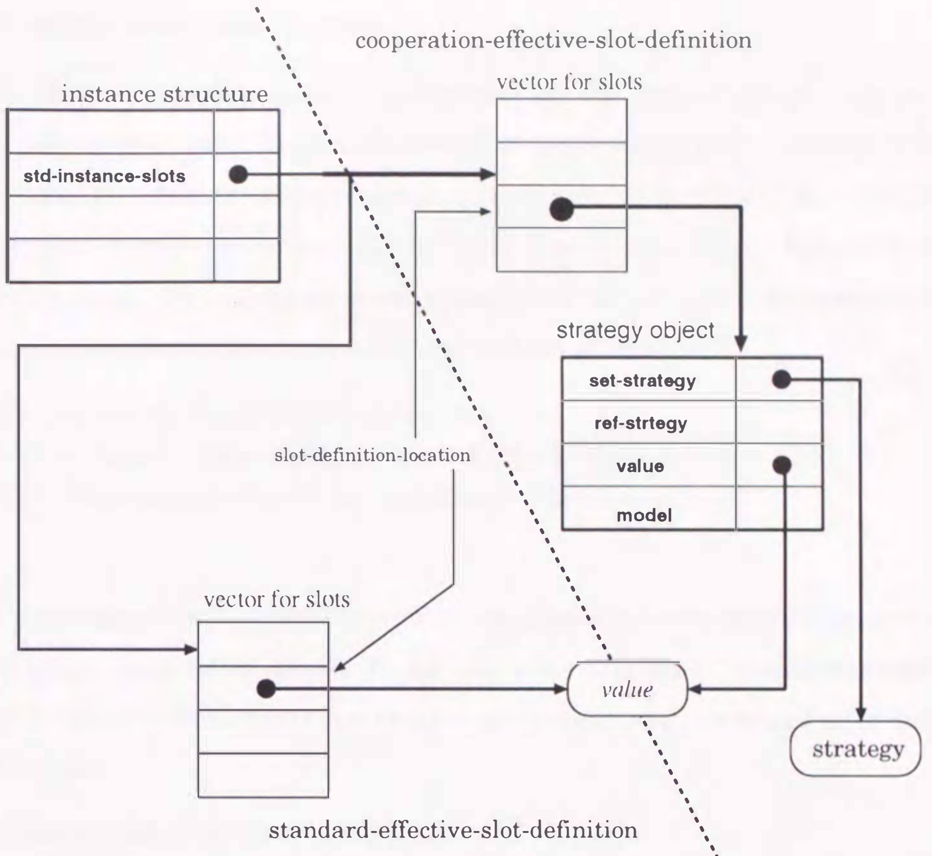


Figure 5.3: slot structure

All classes must have a metaclass that is either the same metaclass of their superclasses or a *valid* metaclass. The generic function: `validate-superclass` checks its validness whenever a new class is defined. Thus we must add a method for our agent-metalevel-class.

```
(defmethod pcl::validate-superclass
            ((class agent-metalevel-class) (superclass pcl::standard-class))
      t)
```

With this method, we can define any agent classes as subclass of `standard-class`. They use `cooperation-effective-slot-definition` for specific slots.

add slot-access-using-class method

In CLOS, the most primitive access/assign functions are `slot-value-using-class` and `(setf slot-value-using-class)`[2] respectively. Other slot accessors use them internally. Thus, now we must define two methods for accessing and updating a slot of agent class. `slot-value-using-class` dispatches with an argument: slot-definition. Usual class uses `pcl::standard-effective-slot-definition`. We add `cooperation-standard-effective-slot-definition` as a subclass of `pcl::standard -effective-slot-definition` as following.[3]

```
(defclass cooperation-standard-effective-slot-definition
    #+CMUCL(pcl::standard-effective-slot-definition) ; if the system is CMUCL
    #-CMUCL(standard-effective-slot-definition) ; otherwise
    )
```

The following method is added for `cooperation-standard-slot-definition`. It is invoked during the class initialization process. In this case, a slot that has : `cooperative-strategy` keyword parameter of a subclass of `agent-class` uses `cooperation-standard-slot-definition` as its descriptor.

```
(defmethod pcl::effective-slot-definition-class
                ((class agent-metalevel-class) initargs)
        (if (member :cooperation-strategy initargs)
                (pcl::find-class 'cooperation-standard-effective-slot-definition)
                (pcl::find-class 'pcl::standard-effective-slot-definition)))
```

The main difference is that the stored value in a slot is wrapped by the strategy object whose definition is described below. The first one is for value assignment.

```
(defmethod (setf pcl::slot-value-using-class)
    ((new-value t) (class agent-metalevel-class)
     object (slotd comm-standard-effective-slot-definition))
  ;; assign the new-value to slotd of object in class
  (let ((location (pcl::slot-definition-location slotd))
```

[2] `(setf slot-value-using-class)` is a symbol whose name includes braces and a space.

[3] In CLOS/MOP system, there is another slot definition class: `standard-direct-slot-definition`. Since it is parallel to `standard-effective-slot-definition`, we ignore it in this thesis.

```
        (slot-instance))
    (cond ((typep (pcl::%instance-ref (pcl::std-instance-slots object) location)
                  'communication-strategy)
           (let* ((slot (pcl::%instance-ref (pcl::std-instance-slots object) location)))
             (update-value slot new-value) ; model (history) is updated in update-valuue
             (when *out-of-local-computation-p*
               (funcall (set-strategy slot) object slot-instance slotd))))
          (t (setf slot-instance
                   (make-instance (strategy-class slotd)
                                  :history (make-array (memory-size slotd)
                                                       :initial-element 0.0)
                                  :value new-value)))))
  new-value)
```

The rest is for its reference.

```
(defmethod pcl::slot-value-using-class
    ((class agent-metalevel-class)
     object
     (slotd cooperation-effective-slot-definition))
  (let* ((location (pcl::slot-definition-location slotd))
         (strategy-object ...)) ;; same as the original method
    (if (typep (pcl::%instance-ref (pcl::std-instance-slots object) location)
               'communication-strategy)
        (progn (funcall (ref-strategy strategy-object) slot)
               (value strategy-object))
        ;; signal unbound error
        (pcl::slot-unbound class object (pcl::slot-definition-name slotd)))))
```

unboundness checking

In the initialization steps in `make-instance`, a strategy instance is created as the value of a slot. This means the standard method of `slot-boundp` returns `t` even if it has not been used. We define the following method for communication-strategy-slot-class. It call `slot-boundp-using-calss`. Thus we add new method as well as slot-value-using-class, which invokes `slot-boundp` for value in the strategy object.

5.2.3 interface to programmer

Now we must provide an interface to problem-solving programmers. At first we provide a new macro for class definition: *defagent*. Its task is adding :metaclass option to class options and add some slots. Its definition is the following.

```
(defmacro defagent (class-name super-class-list &optional slot-defs &rest rest)
  `(defclass ,class-name
          ,(if (member 'agent-class super-class-list)
               super-class-list
               (cons 'agent-class super-class-list))
        ,slot-defs
      ,@(cons '(:metaclass agent-meta-class) rest)))
```

Therefore the following form:

```
(defagent an-agent-class ()
  (...))
```

is expanded as:

```
(defclass an-agent-class (agent-class)
  (...)
  (:metaclass agent-class))
```

`defagent` can hide the names of both the metaclass and slots for communication strategies.

make-instance

In CLOS, making an instance of a particular class is performed by `make-instance`. Usually its arguments are for slot initialization.

Our communication strategies require knowledge about a communication cost. It depends on each environment. Thus when making an agent, we must give a cost function to the agent as well. However arguments required to the function depend on a strategy. Furthermore, an agent may use more than one strategies in our implementation. Thus we need a way to distinguish cost functions. Our solution is using a unique keyword for `make-instance`. The keyword is built as a concatenation of 'cost-function' and the name of the strategy class. Thus if we use `spatial-control` as a strategy for exchanging the value in slot `foo` in user-defined class: `C`, and use `temporal-control` as a strategy for slot `woo`, its instance is created by:

```
(make-instance 'C
   :communication-cost-for-spatial-control #'(lambda (num-of-packet) ...)
   :communication-cost-for-temporal-control #'(lambda (frequency) ...)
)
```

These keyword parameters are processed at `initialize-instance` method defined for `agent-class`. As we described earlier, the former lambda function is stored into `cost-function` slot of the instance of class `spatial-control` that is assigned to the slot: `foo` of the instance.

5.3 Applications

In this section, we investigate the applicability of the implementation by using two programs. The first one is the TSP program that we used in Chapter 4. The later is shared object management in distributed environments.

5.3.1 traveling salesman problem

With this framework, writing TSP program in a separated way is straightforward. Both the spatial connectivity control strategy and the frequency control strategy should be invoked when a slot renewal is occurred. The structure of the history depends on the strategy. Its definition is included in the definition of strategy classes.

```
(defagent search-agent ()
  ((threshold ; slot definition
    :set-strategy spatial-control)
  ...))

(defclass spatial-control (communication-strategy)
 ((range :accessor range :initform 0 :initarg :range :type fixnum)
  (neighbor-list :accessor neighbor-list :initform nil)
  (recommended-size :accessor recommended-size :initform 1
                              :initarg :recommended-size :type fixnum)))
```

```
(defmethod set-strategy ((strategy spatial-control) instance)
  ;; range slot holds the new optimal range
  (setq (range strategy) (select-best-range (model strategy)))
  ;; send the body slot
  (send (make-instance 'spartial-control-message
                        :body (list (class-name instance)
                                    (value strategy)))
        (choose-receivers (range strategy) (neighbor-list strategy))))


;; In the program that uses searching-agent,
  (make-instance search-agent
                 :communication-cost-for-spartial-strategy
                 #'cost-estimation-function)

(defmethod dispatcher ((class spatial-control) slot instance message)
  (if (spatial-control-class-message-p message)
      (when (betterp (body message) instance)
        ;; update-value is an internal method for communication-strategy
        (update-value class slot instance new-value))))
```

distinction of received data

In this program, a received threshold is assigned to the local threshold slot. If we used `(setf threshold)` for the assignment, a communication strategy would be invoked once more. It would cause repetition of communication. Though the loop, however, would be terminated since the utility of communication decreased by the increase of homogeneity of agents, if we want to avoid the loop, we should provide a raw assignment method. But the renewal should be a part of metalevel computation. Therefore receiving is not visible to the problem-level program but a task of metalevel computation invoked by the dispatching process at metalevel. It will use a raw level assignment method that does not invoke any communication strategy, which is called `update-value` in the above program.

5.3.2 shared object management

shared object management Most distributed programs use shared objects among processes. They require strong consistency. This is the most important difference from threshold in the previous example. From our point of view, threshold requires only weak consistency; the consistency is required for effective execution. Objects with strong consistency can be made in two ways in distributed environments. First approach is using *virtual shared memory* [Li86, Lh89]. The object is accessed by its address in the same way as local objects. In this system, memory pages are shared by all nodes. A copy of each page is located where it is accessed. Thus a running program has locality in memory access, it reduces the inter-node communication costs.

The second approach is based on a distributed algorithm. The object is implemented as local object on each node. They are identical; they have the same value. If a renewal is required, by broadcasting notification, all objects are updated as atomic action. This is a message-passing style implementation.

Some virtual shared memory approaches use parallel cache algorithm (f.e. Snoopy cache) to hold coherency amang copies. This algorithm distribute copies at first step. The number of copies does not change. Thus it can be consider a variation of distribute algorithm based approach.

The main difference between these approaches is the number of identical copies. Most viretual shared memorry approaches do not make copies of an object. Thus though the update's cost is low, if the locality is low, the accessing costs will be high. On the other hand, the second approach requires broadcasting whenever the renewal occurrs. We can imagine the adaptive approach: change the locations and the number of copies. These decisions should be based on the history of access/update pattern if we make it adaptive dynamically. Therefore our history based approach will be useful for this problem. Shared object management can be interpreted as a problem of cooperation. Note that it is rather MAS than DPS, since each agent' local desires conflict with each other.

We should note that some papers investigate control method for changing the implementation of objects by program analysis (for example [KL95]). But it uses static, pre-execution

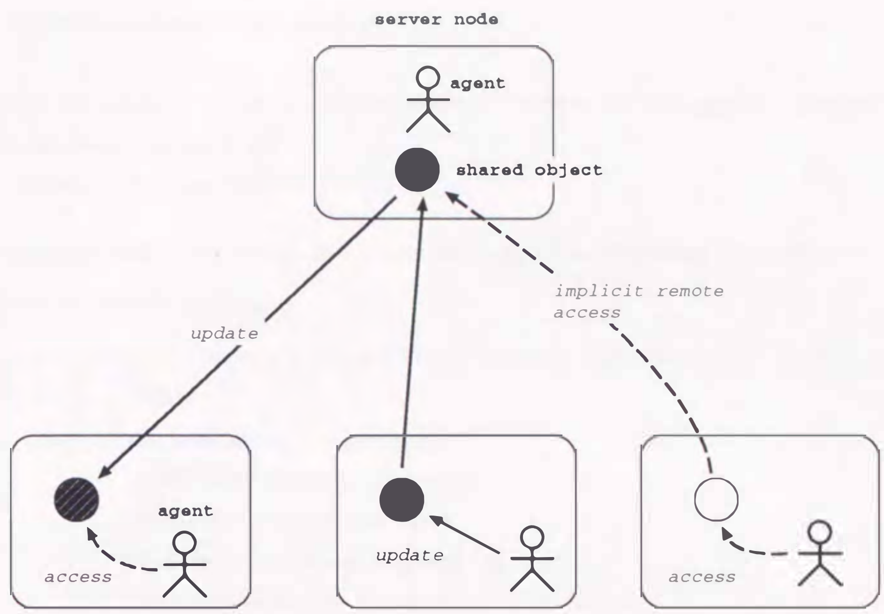


Figure 5.4: shared object distribution

information. Quantitative properties are ignored.

Here we describe a strategy that control the number of copies in a centralized manner [YNU95]. A pre-fixed node becomes the server. The others become owners or clients.

```
(defagent parallel-worker ()
  ((shared-object
     :cooperative-strategy shared-object-manager/central-manner)
   ...))

(defclass shared-object-manager/central-manner (communication-strategy)
  ((server-id :type host-id)
   (member-list :type list)
   (owner-p :type boolean))

(defmethod server-p ((self shared-object-manager/central-manner))
  (= (server-id self) (id self)))

(defmethod set-strategy ((strategy shared-object-manager/central-manner) instance)
  (cond ((server-p strategy) (broadcast-update-request strategy))
```

```
        (t (send-update-request strategy))))

(defmethod ref-strategy ((strategy shared-object-manager/central-manner) instance)
  (cond ((owner-p instance) nil)
        (t (send-reference-request strategy))))
```

To receive messages, we need one more method. The following `dispatcher` should be invoked from `receive` function.

```
(defmethod dispatcher ((strategy shared-object-manager/central-manner) instance message)
  (cond ((server-p strategy)
         (cond ((request-message-p message)
                (send-value strategy message))
               ((update-message-p message)
                (update-slot-internal strategy message)
                (broadcast-message strategy)
                (receive-all-ack strategy)))
         ((and (owner-p strategy) (update-request-p message))
          ;; ... update and return ack to server
          )
         (t (error)))))
```

To eliminate the central controller, each process should have a more cooperative protocol. Modeling others that would use not only history of communication but also the result of program analysis or the description of other agents' mental models will be required.

5.4 Discussion

As we explain above, this framework can describe many kinds of communication strategies. Though we omit the detail here, we can also use this implementation to use temporary cache method that is mentioned in Chapter 2. Now, we will investigate some demerits and difficulties of this framework in the next section.

5.4.1 restriction of meta-object protocol approach

The main restriction of this implementation comes from MOP approach. MOP is not a reflectional computation mechanism that can change all of the base-level computation. Therefore an agent can not change the role of itself by any communication strategy. If we want to let agent do it, more interface between a problem-level program and a metalevel program is required. But it spoils the merit of separate description. This restriction will be crucial when we want to built more autonomous agents that has a planner in it in order to decide its future plan.

5.4.2 role differentiation by method combination

On the other hand, some modifications to base programs can be done by method combination. For example, we have proposed the spatial connectivity control strategy on two structures. It requires an agent to change its role from a computing agent to a dedicated information collector. This changes is done as:

1. stop invoking original method.
2. register a new method for collecting information
3. inform this change to other agent

The main issue is how to change the method body. CLOS has a solution which use method combination. The change process is

> *If I should become an information collector, I run a method for collecting information whanever I resume.*
> *If I should become a searching agent, I run a method for searching whanever I resume.*

This is a kind of method dispatching based on the result of the method priority computation. This method selecting computation differs from normal class-hierarchy based computation. But CLOS provides a way to define new, arbitrary method combinations.

In this framework, operators (method) that are described in an imperative style are invoked by the result of method selecting computation. By using a language extension, we can write it down in an imperative or declarative manner. When an agent `A` resumes to run a method `M`, the method with the highest priority in all methods in `M` at `A`'s point of view is selected, where the `M` that does nothing for collecting information is defined in a superclass of every agent class that is defined with `def-agent`. It is a default behavior of every agent. It is natural to inherit it and to select appropriate method dynamicall by using method combination.

This framework will be implemented with `define-method-combination` and more protocol definition between application programmer and the system.

More drastic approach is mixing a MOPed OOPL with logic-based language extension. A planner-based description can be merged more flexiblely. We plan the use of Scheme [CR91] with tiny-CLOS (subset of MOP in Scheme) [Kic91, Gal95] and an tool for logic programming. Since modern Scheme implementations support parallel programming, inter-processor communication, real-time GC and so on, they will be a good platform for DAI/MAS testbed.

5.4.3 efficiency

MOP based-languages has an issue; its efficiency. In languages that supports MOP, every slot access consists of a sequence of some methods. Comparing with a structure in traditional languages, an access to a field in the structure is transformed to a machine code for loading the content at an address with an offset. Sometimes the time for a reference of a slot becomes ten times slower than one for a reference of a field of a structure. But, as MOP researchers say, the language efficiency is not an issue of the language itself but one of implementation. For example, CMUCL optimizes CLOS code if the metaclass used in a program is standard-meta-object. In our approach, since metaclass of slot is fixed during its execution, unfolding metalevel code into a sequence of flat procedure calls by compiler could be possible. In this case, we can avoid computation cost of MOP in execution time. For example, Masuhara et al. have proposed a method with partial evaluation of meta-level computation in ABCL/R2 and ABCL/R3 [MMWY92, MWIY92, MMAY95].

Anyway, flexibility to change the program's behavior is important in distributed systems, since programmers can not forecast its exact execution situation.

5.5 Summary

1. The communication strategies are implemented as a metalevel computation where the base program corresponds to the application program.

2. MOP is a useful method to extend a base language for this purpose.

3. Our communication strategies are thought as a set of the extensions to semantics of reference and assignment to an agent-local variable. Thus CLOS MOP provides a straightforward implementation of our strategies.

4. We illustrated the implementations of some communication strategies.

5. We showed some restrictions of our framework. One is caused by the restricted reflectional power of MOP that can not change the problem level programs. Another one is efficiency issue. We also showed some ideas to solve these issues.

Chapter 6

Conclusion

In this thesis, we presented communication strategies based on partial histories of agents for modeling their environment to select efficient communication structures dynamically. The experiments showed that the strategies brought good communication structures to autonomous agents. We proved that agent's local history as a qualitative model of revision of information, which is a measure of execution, is useful for MAS.

Though there are some restrictions such as the implemented strategies assuming homogeneity of agents, the simplicity of combining some pieces of information, and the information of the communication cost function, we think that these strategies can be used in many applications that acquire new information in execution time, if we can find information which value increases monotonously and can build a communication cost function. These would contain distributed database systems that replicate data.

The reason of good results from local-history based estimation method is that agents in systems we used can be assumed homogeneous. Thus we need not to build an exact model of other agents. This implies the assumption that their goals do not conflict with each other. It is not useful for MAS architecture but DAI. The history-based expectation mechanism, however, could apply to not only homogeneous environments but also heterogeneous ones. The history of the revision of information at other agents in current implementations is not separated from its own history. Agents exchange the information with each other and update its history with the received information. But in heterogeneous network, the speration of histories would become an important problem. The implementation and the evaluation of strategies based on separated histories are a future plan. It will also work on heterogeneous agents.

In this thesis, we proposed a cooperation scheme on distributed systems. However cooperative processing is not only useful on distributed systems but also on concurrent systems. One example that requires cooperation, even if the communication cost can be ignored, is a parallel search based on genetic algorithms. A search process would fall in a local minimum position by over-distribution of the best code at each step. Thus broadcasting the best code pattern does not necessarily lead to the optimal form of computation. The same discussion is held on heuristic-base parallel search. In these examples, cooperation changes the way of sharing information between agents. Thus we can define cooperation as methods for selecting an appropriate structure of processing elements. Its application is not restricted to distributed systems. We think that local-history based methods like ours will be useful for building schemes on such systems.

Our study assumes that the intention of a programmer is presented in a program but not a specification. Therefore we consider about neither rule-based or operator-based description nor MAS. Thus our approach has a restriction necessarily for building strongly autonomous systems. But we think there is a hierarchy of autonomy. At the top of the hierarchy, the unit is human or a very autonomous agent. They can be described well by the term of belief, desire, and intention(they are called as BDI theory). But the bottom level the description of the goal of a computational unit is decomposed to a sequence of orders. If we assume the number of computation unit in the real world becomes very large, to use them effectively, pulling parallelism off is the important issue, even if the platform is distributed and thus we can not ignore the communication cost on them. Since there will be a hierarchy of physical closeness of computational units, our approach would be used in the low-level of problem-solving strategy's hierarchy.

Of course, history-based estimation method will be useful in high-level planning. It will require probabilistic reasoning. The emergence of intelligence is one of the important research themes in Artificial intelligence. Recent studies about emergent computation investigate a way to make information processing machine from a pool of simple units [For91, FM90]. Making more intelligent system from units by a kind of evolution requires a meta-calculation about utility like stability or uniqueness. Therefore selecting the input of itself and selecting related modules is crucial. The issue about computation of connectivity between the units will be emerged once again [Lan90, KHH89]. Therefore more study about connectivity should be expected.

Acknowledgments

I would like to thank to Professor Kazuo Ushijima at Kyushu University for supporting this research and improving the quality of this thesis. I am very grateful to Professor Akifumi Makinouchi, Professor Ryuzo Hasegawa and Professor Kotaro Hirasawa at Kyushu University. Their valuable commments are gratefully acknowledged.

I would like to express my apprecation to Associate Professor Norihiko Yoshida at Kyushu University for discussion about DAI, MAS, OOPL, and direction of this research for long years.

I would also like to note two graduate students: Hiroomi Yamamura, the implementer of the freqeuncy control strategy and Kenji Yamasaki, who impelemented the core part of CLOS MOP-based system.

Bibliography

[ACM95a] ACM. *ACM SIGPLAN NOTICES*, volume 30, number 10. ACM Press, October 1995.

[ACM95b] ACM. *OOPSLA '95 Conference Proceedings*. Austin, 1995. Reprinted as [ACM95a].

[AG92] Nicholas M. Avoris and Les Gasser, editors. *Distributed Artificial Intelligence: Theory and Praxis*. Kluwer Academic Publishers, 1992.

[Axe84] Robert Axelrod. *The Evolution of Cooperation*. Basic Books, New York, 1984.

[BG88] Alan H. Bond and Les Gasser, editors. *Readings in Distributed Artificial Intelligence*. Morgan Kaufmann, 1988.

[BJD85] M. Benda, V. Jagannathan, and R. Dodhiawalla. On optimal cooperation of knowledge sources. Technical report, Boeing AI Center, 1985.

[BP95] Edward A. Billard and Joseph C. Pasquale. Adaptive Coordination in Distributed Systems with Delayed Communication. *IEEE Trans. Sys. Man Cyb.*, 25(4):546–554, April 1995.

[CG89] N. Carriero and D. Gelernter. Linda in context. *Comm. ACM*, 32(4):444–458, April 1989.

[CG90] Nicholas Carriero and Davis Gelernter. *How to Write Parallel Programs – A First Course*. The MIT Press, 1990.

[Chi93] Andrew A. Chien. *Concurrent Aggregates*. The MIT Press, 1993.

[CL88] R. Conry, S. Meyer and V. Lesser. Multistage negotiation in distributed planning. In Bond and Gasser [BG88], chapter 5.3, pages 367–384.

[CR91] Eilliam Clinger and Jonathan Rees (editors). Revised[4] report on the algorithmic language Scheme. Technical report, November 1991.

[DB93] Jiri Dvorak and Horst Bunke. Usijng clos to impelement a hybrid knowledge representation tool. In Paepcke [Pae93a], chapter 12, pages 295–320.

[DLC87a] Edmund H. Durfee, Victor R. Lesser, and Daniel D. Corkill. Coherent Cooperation Among Communicating Problem Solvers. *IEEE Transactions on Computers C-36*, pages 1275–1291, 1987. Reprinted in [BG88], pp.268–284.

[DLC87b] Edmund H. Durfee, Victor R. Lesser, and Daniel D. Corkill. Cooperation through communication in a distributed problem solving network. In Huhns [Huh87], chapter 2, pages 29–58.

[DM89] Edmund H. Durfee and Thomas A. Montgomery. MICE: A flexible tested for intelligent coordination experiments. In *Proceedings of the Ninth Workshop on Distributed Artificial Intelligence*, pages 25–40, 1989.

[DM91a] Yves Demazeau and Jean-Pierre Müller, editors. *Decentralized A.I. 2*. North-Holland, Saint-Quentin en Yvelines, France, 1991. Proceedings of the Second European Workshop on Modelling Autonomous Agents in A Multi-Agent World(1990).

[DM91b] Edmund H. Durfee and Thomas A. Montgomery. Coordination as Distributed Search in a Hierarchical Behavior Space. *IEEE Trans. Syst. Man Cybern.(Special Issue on Distributed AI)*, 21(6):1363–1378, November/December 1991.

[DS88] R. Davis and Reid G. Smith. Negotiation as a metaphor for distributed problem solving. In Bond and Gasser [BG88], chapter 5.1, pages 331–356.

[Dur88] Edmund H. Durfee. *Coordination of Distributed Problem Solvers*. Kluwer Academic Publishers, 1988.

[EM88] Robert Engelmore and Tony Morgan, editors. *Blackboard Systems*. Addison-Wesley, 1988.

[EPT94] David Edmond, Mike Papazoglou, and Zahir Tari. Using Reflection as a Means of Achieving Cooperation. In *International Symposium on Fifth Generation Computer Systems 1994 Workshop on Heterogeneous Cooperative Knowledge-bases*, pages 17–31. Institute for New Generation Computer Technology, December 1994.

[FB88] Jacques Ferber and Jean-Pierre Briot. Design of a Concurrent Language for Distributed Artificial Intelligence. In *Proceedings of the International Conference of Fifth Generation Computer Systems*, pages 755–762, 1988.

[FC91] Jacques Ferber and P. Carle. Actors and Agents as Reflective Concurrent Object:a Mering-IV Perspective. *IEEE Transactions on Systems, Man, and Cybernetics*, 21(6):1420–1436, November/December 1991.

[FKR95] Maier Fenster, Sarit Kraus, and Jeffrey S. Rosenschein. Coordination without Communication: Experimental Validation of Focal Point Techniques. In Victor R. Lessor, editor, *ICMAS-95 Proceedings First International Conference on Multi-Agent Systems*, pages 102–108, San francisco, June 1995. The AAAI Press/The MIT Press.

[FL77] R. D. Fennell and Victor R. Lesser. Parallelism in Artrificial Intelligence Problem Solving: A Case Study of Hearsay-II. *IEEE Trans. Computers,*, C-26(2):98–111, 1977. Also reprinted in [BG88].

[FM90] Stephanie Forrest and John H. Miller. Emergent behavior in classifier systems. *Physica D*, 42:213–227, 1990. Reprinted in [For91].

[For91] Stephanie Forrest, editor. *Emergent Computation*. The MIT Press, 1991.

[Fox88] Mark S. Fox. An organizational view of distributed systems. In Bond and Gasser [BG88], pages 140–150.

[Gal95] Erick Gallesio. STk. Universite de Nice, ftp://kaolin.unice.fr/pub/, 1995. Latest version is 3.0, MIT AI Repository is its mirror site.

[Gas92a] Les Gasser. Boundaries, identity, and aggregation: Plurality issues in multiagent systems. In Werner and Demazeau [WD92], pages 199–213.

[Gas92b] Les Gasser. Object-Based Concurrent Programming and Distributed Artificial Intelligence. In Avoris and Gasser [AG92], pages 81–107.

[GBH87] Les Gasser, Carl Braganza, and Nava Herman. Implementing distributed artificial intelligence systems using mace. In *Proceedings of the Third IEEE Conference on Artificial Intelligence Applications*, pages 315–320, 1987. Reprinted in [BG88], pp.445-450.

[Gel85] David Gelernter. Generative communication in linda. *ACM Tran. Prog. Lang. Syst.*, 7(1):86–112, January 1985.

[GH89] Les Gasser and Michael N. Huhns, editors. *Distributed Artificial Intelligence Volume II*. Pitman/Morgan Kaufmann, London, 1989.

[GRHL89] Les Gasser, Nicholas F. Rouquette, Randall W. Hill, and John Lieb. Representing and using organizational knowledge in distributed AI systems. In Gasser and Huhns [GH89], chapter 3, pages 55–78.

[HB91] Michael N. Huhns and David M. Bridgeland. Mulitagent truth maintenance. *IEEE Trans. Syst. Man Cybern.(Special Issue on Distributed AI)*, 21(6):1437–1445, 1991.

[Hew77] Carl Hewitt. Viewing control structures as patterns of passing messages. *Artificial Intelligence*, 8, 1977. North-Holland.

[HG93] Bernardo A. Huberman and N. S. Glance. Social dilemmas and fluid organizations. In *in printing*, pages 496–505, 1993.

[HH87] Bernardo A. Huberman and Tad Hogg. Phase transition in artificial intelligence systems. *AI-journal*, 23(2), 1987.

[HH88] Bernardo A. Huberman and Tad Hogg. The behavior of computational ecologies. In Huberman [Hub88], pages 77–115.

[HM84] Joseph Y. Halpern and Yoram Moses. Knowledge and common knowledge in a distributed environment. In *Proceedings of the Third Annual ACM Symposium on Principles of Distributed Computing*, pages 50–61, 1984.

[HM90] Joseph Y. Halpern and Yoram Moses. Knowledge and common knowledge in a distributed environment. *Journal of the ACM*, 37(3):549–587, July 1990. Riveted version of IBM Research Report IBM RJ 4421(1984).

[Hub88] Bernardo A. Huberman, editor. *The Ecology of Computation*. Elsevier Science Publishers B.V.(North-Holland), Amsterdam, 1988.

[Hub90] Bernardo A. Huberman. The performance of cooperative processes. *Physica D*, 42:38–47, 1990. Reprinted in [For91].

[Hub92] Bernardo A. Huberman. The value of cooperation. In Masuch and Warglien [MW92], chapter 10, pages 235–243.

[Huh87] Michael N. Huhns, editor. *Distributed Artificial Intelligence*. Morgan Kaufmann, 1987.

[HW93] Tad Hogg and Colin P. Williams. Solving the Really Hard Problmes with Cooperative Search. In *AAAI-93*, pages 231–236. AAAI, AAAI Press/The MIT Press, 1993.

[IGY92] Toru Ishida, Les Gasser, and Makoto Yokoo. Organization Self-Design of Distributed Production Systems. *IEEE Transactions on Data and Knowledge Engineering*, 4(2):123–134, 1992.

[Ish93a] Toru Ishida, editor. *MultiAgent and Cooperative Computation II*, volume 5 of *lecture note/software*. Kindaikagakusha, 1993.

[Ish93b] Toru Ishida. Realtime bidirectional search. In *MultiAgent and Cooperative Computation II* [Ish93a], pages 121–135.

[Ish95] Toru Ishida. Discussion on agents. *Journal of japanese Society for Artificial Intelligence*, 10(5):663–667, September 1995. in Japanese.

[Kau93] Stuart A. Kauffman. *The Origins of Order*. Oxford University Press, 1993.

[KC93] Yasuhiko Kitamura and Zheng Bao Chauang. A cooperative search scheme for dynamic problems. In Ishida [Ish93a], pages 137–147.

[KdRB91] Gregor Kiczales, Jim des Rivières, and Daniel G. Bobrow. *The Art of the Metaobject Protocol*. The MIT Press, 1991.

[Kee89] Sonya E. Keene. *Object-Oriented Programming in Common Lisp — A Programmers's Guide to CLOS —*. Symbolics, Inc., 1989.

[KG94] Taha Khedro and Michael R. Genesereth. Modeling multiagent cooperation as distributed constraint satisfaction problem solving. In A. Cohn, editor, *ECAI94*, pages 249–253. John Wiley & SOns, Ltd., 1994. 11th European Conference on Artificial Intelligence.

[KHH89] Jeffrey O. Kephart, Tad Hogg, and Bernardo A. Huberman. Dynamics of computational ecosystems: Implications for DAI. In Gasser and Huhns [GH89], chapter 4, pages 79–95.

[Kic91] Gregor Kiczales. Tiny CLOS. Xerox, ftp://arisia.xerox.com/pub/openimplementations/, 1991.

[KL95] Anders Kristensen and Colin Low. Problem-Oriented Object Memory: Customizing Consistency. In *OOPSLA'95 Conference Proceedings* [ACM95b], pages 399–413. Reprinted as [ACM95a].

[Kni93] Kevin Knight. Are many reactive agents better than a few deliberative ones? In *Proceedings of the 1993 International Joint Conference on Artificial Intelligence*, pages 432–437, 1993.

[KTTO93] Yasuhiko Kitamura, Ken'ich Teranishi, Shoji Tatsumi, and Takaaki Okumoto. Communication control in distributed search. In *IPSJ SIG Notes AI-93-89*, pages 41–50, August 1993. in Japanese.

[Lan90] Christopher G. Langton. Computation at the edge of chaos: Phase transitions and emergent computation. *Physica D*, 42:12–37, 1990. reprinted in [For91].

[LC88] Victor Lesser and D. Corkill. Functionally accurate, cooperative distributed systems. In Bond and Gasser [BG88], chapter 4.3.1, pages 295–310.

[LE80] Victor R. Lesser and Lee D. Erman. Distributed interpretation: A model and experiment. *IEEE Transactions on Computers*, 29(12):1144–1163, 1980. Reprinted in [BG88].

[Les90] Victor R. Lesser. An Overview of DAI: Viewing Distributed AI as Distributed Search. *Journal of Japanese Society for Artificial Intelligence*, 5(4):392–400, 1990.

[Les91] Victor R. Lesser. A retrospective view of FA/C distributed problem solving. *IEEE Trans. Syst. Man Cybern.(Special Issue on Distributed AI)*, 21(6):1347–1361, November/December 1991.

[Lh89] Kai Li and Paul hudak. Memory coherence in shared virtual memory systems. *ACM Trans. Computing Systems*, 7(4):229–239, November 1989.

[Li86] Kai Li. *Shared Virtual Memory on Loosely Coupled Multiprocessors*. PhD thesis, Yale University, September 1986.

[LLARKS85] E.L. Lawer, J.K. Lenstra, D.B. A.H.G. Ronnoony Kan, and Shmoys, editors. *The Traveling Salesman Problem*. Addison Wesley, 1985.

[LR92] Ran Levy and Jeffrey Rosenschein. A game theoretic approach to distributed artificial intelligence and the pursuit problem. In Werner and Demazeau [WD92], pages 129–146.

[MIT90] Takeo Maruichi, Masaki Ichikawa, and Mario Tokoro. Modeling autonomous agents and their groups. In Yves Demazeau and Jean-Pierre Müller, editors, *Decentralized A.I.*, pages 215–234. North-Holland, Saint-Quentin en Yvelines, France, 1990. Proceedings of the First European Workshop on Modelling Autonomous Agents in A Multi-Agent World (1989).

[MMAY95] Hidehiko Masuhara, Satoshi Matsuoka, Kenichi Asai, and Akinori Yonezawa. Compiling Away the Meta-Level in Object-Oriented Concurrent Reflective Languages using Partial Evaluation. In *OOPSLA'95 Conference Proceedings* [ACM95b], pages 300–315. Reprinted as [ACM95a].

[MMWY92] Hidehiko Masuhara, Satoshi Matsuoka, Takuo Watanabe, and Akinori Yonezawa. Objet-oriented concurrent reflective languages can be implemented efficiently. In *Proceedings of the ACM Conference on Object-Oriented Programming Systems, Languages, and Applications(OOPSLA '92)*, pages 127–144. ACM, 1992.

[MN88] Pattie Maes and Daniele Nardi, editors. *Meta-Level Architectures and Reflection*. North-Holland, 1988.

[MW92] Michael Masuch and Massimo Warglien, editors. *Artificial Intelligence in Organization and Management Theory*. Elsevier Science Publishers B.V., 1992.

[MWIY92] Satoshi Matsuoka, Takuo Watanabe, Yuji Ichisugi, and Akinori Yonezawa. Object-oriented concurrent reflective architectures. In *Object-Based Cocurrnet Computing*, volume 612 of *Lecture Notes in Computer Science*. Springer-Verlag, 1992.

[MWY91] Satoshi Matuoka, T. Watanabe, and A. Yonezawa. Hibrid Group Reflective Architecture for Object-Oriented Cocurrent Reflective Programming. In *Fifth ECOOP*, July 1991.

[Nar90] Shuji Narazaki. Cooperative Processing Model Cellula based on fields. Master's thesis, Kyushu University, March 1990. in Japanese.

[Nar95] Shuji Narazaki. Effects of view ranges of agents in pursuit problem. In Kouichi Hashida, editor, *MultiAgent and Cooparative Computation IV*, volume 13 of *lecturenote/software*, pages 49–56. Kindaikagakusha, November 1995. Proceedings of JSSST MACC'94 workshop.

[NT90] Chisato Numaoka and Mario Tokoro. Distributed aritificial intelligence and programming languages. *JOurnal of japanese SOciety for Aritificial Intelligence*, 5(5):441–421, July 1990.

[Num92] Chisato Numaoka. Conversation for organizational activity. In Werner and Demazeau [WD92], pages 189–198.

[NY93] Shojiro Nishio and Akinori Yonezawa, editors. *Object Technologies for Advanced Software*, 742, Kanazawa, Japan, 1993. JSSST, Springer-Verlag. First JSSST International Symposium.

[NYY94] Shuji Narazaki, Hiroomi Yamamura, and Norihiko Yoshida. Strategies for selecting communication structures in cooperative search. In *International Symposium on Fifth Generation Computer Systems 1994 Workshop on Heterogeneous Cooperative Knowledge-Bases*, pages 155–166, December 1994. Reprinted as [NYY95].

[NYY95] Shuji Narazaki, Hiroomi Yamamura, and Norihiko Yoshida. Strategies for selecting communication structures in cooperative search. In ?, volume - of *Lecture Notes in Aritificial Intelligence*. Springer-Verlag, 1995.

[OIT93] Hideaki Okamura, Yutaka Ishikawa, and Mario Tokoro. Metalevel Decomposition in AL-1/D. In Nishio and Yonezawa [NY93], pages 110–144. First JSSST International Symposium.

[Osa93] Ei-Ichi Osawa. Adaptive cooperation schemes coping with dynamic problem space. In Ishida [Ish93a], pages 105–120. in Japanese.

[Pae93a] Andreas Paepcke, editor. *Object-Oriented Programming The CLOS Perspective*. The MIT Press, 1993.

[Pae93b] Andreas Paepcke. User-Level Language Crafting: Introducing the CLOS Metaobject Protocol. In *Object-Oriented Programming The CLOS Perspective* [Pae93a], chapter 3, pages 65–99.

[Pea84] Judea Pearl. *Heuristics – intelligent search strategies for computer problem solving*. Addison-Wesley, 1984.

[Poh71] I. Pohl. Bi-directional search. *Machine Intelligence*, 6:127–140, 1971.

[RB89] Jeffrey S. Rosenschein and John S. Breese. Communication-free interactions among rational agents: A probabilistic approach. In Gasser and Huhns [GH89], chapter 5, pages 99–118.

[RGG86] Jeffrey S. Rosenschein, M. Ginsburg, and Michael R. Genesereth. Cooperation without communication. In *Proceedings AAAI-86*, pages 51–57. AAAI, 1986. Reprinted in [BG88], pp.220–226.

[S+90] Guy L. Steel Jr. et al. *Common Lisp the Language*. DEC press, second edition, 1990.

[SD92] Young-Pa So and Edmund H. Durfee. A Distributed Problem-solving Infrastructure for Computer Network Management. *International Journal of Intelligent & Cooperative Information systems*, 1(2):363–392, June 1992.

[Sim81] Herbert A. Simon. *The Sciences of the Artificial*. The MIT Press, Boston, second edition, 1981.

[SM89] Larry M. Stephens and Matthias Merx. Agent organization as an effector of DAI system performance. In *Proceedings of the Ninth Workshopon Distributed Artificial Intelligence*, pages 263–292, 1989.

[SRSF91] Katia P. Sycara, Steven F. Roth, Norman Sadeh, and Mark S. Fox. Distributed constrained heuristic search. *IEEE Trans. Syst. Man Cybern.(Special Issue on Distributed AI)*, 21(6):1446–1461, 1991.

[Sta89] Susan Leigh Star. The structure of ill-structured solutions: Boundary objects and heterogeneous distributed problem solving. In Gasser and Huhns [GH89], chapter 2, pages 37–54.

[WD92] Eric Werner and Yves Demazeau, editors. *Decentralized A.I. 3*. Elsevier Science Publishers B.V., 1992.

[Wer92] Eric Werner. The design of multi-agent systems. In Werner and Demazeau [WD92], pages 3–28.

[YDIK92] Makoto Yokoo, Edmund H. Durfee, Toru Ishida, and Kazuhiro Kuwabara. Distributed constraint satisfaction for formalizing distributed problem solving. In *Proceedings of the Twelfth IEEE International Conference on Distributed Computing Systems*, pages 614–621, 1992.

[YN90] Norihiko Yoshida and Shuji Narazaki. A cooperation and communication framework for distributed problem solving. In *Proceedings of IEEE 2nd International Conference On Tools For Artificial Intelligence*, pages 530–536. IEEE, 1990.

[YN91] Norihiko Yoshida and Shuji Narazaki. A Distributed Processing System for the Cooperation Model 'Cellula'. *Transactions of Information processing Society of Japan*, 32(7):906–913, 1991.

[YNU95] Kenji Yamasaki, Shuji Narazaki, and Kazuo Ushijima. Imprementation of Cooperative Processing with Metalevel Computation. *IPSJ SIG Notes PRG*, 95(82):145–152, August 1995. in Japanese.

[Yok93] Yasuhiko Yokote. Kernel structuring for object-oriented operating systems: The aperotos approach. In Nishio and Yonezawa [NY93], pages 145–162. First JSSST International Symposium.

[Yok95] Makoto Yokoo. An overview of distributed search. *Computer Software*, 12(1):33–42, 1995. in Japanese. Japan Society for Software Science and Techonology.

[YSTH87] Akinori Yonezawa, Etsuya Shibayama, Toshihiro Takada, and Yasuaki Honda. Modelling and programming in an object-oriented concrrent language abcl/1. In Akinori Yonezawa and Mario Tokoro, editors, *Object-Oriented Concurrent Programming*, pages 55–89. The MIT Press, 1987.

Index

業績一覧

論文

1. 吉田紀彦, 楢崎修二, 下川俊彦, "協調処理モデル Cellula の分散処理系と支援環境", 並列処理シンポジウム Joint Symposium on Parallel Processing '90 論文集 (平成 2 年 5 月)

2. 吉田紀彦, 楢崎修二, "場と一体化したプロセスの概念に基づく協調処理モデル Cellula", 情報処理学会論文誌 第 31 巻第 7 号 (平成 2 年 7 月)

3. Norihiko Yoshida, Shuji Narazaki, " A Cooperation and Communication Framework for Distributed Problem Solving", Proceedings of IEEE 2nd International Conference On Tools For Artificial Intelligence(平成 2 年 11 月)

4. 吉田紀彦, 楢崎修二, "協調処理モデル Cellula の分散処理系" , 情報処理学会論文誌第 32 巻 第 7 号 (平成 3 年 7 月)

5. 楢崎修二, "分散問題解決のための自律的構造選択戦略", 日本ソフトウェア科学会 MACC'93 論文集「マルチエージェントと協調計算 III」 (平成 4 年 10 月)

6. Shuji Narazaki, Norihiko Yoshida, Hiroomi Yamamura, "Strategies for Selecting Communication Structures in Cooperative Search", International Symposium on Fifth Generation Computer Systems 1994 Workshop on Heterogeneous Cooperative Knowledge-Bases(平成 6 年 12 月)

7. 楢崎修二, "追跡問題における視界の影響", 日本ソフトウェア科学会 MACC'94 論文集「マルチエージェントと協調計算 IV」 (平成 7 年 11 月)

8. Shuji Narazaki, Norihiko Yoshida, Hiroomi Yamamura, "Strategies for Selecting Communication Structures in Cooperative Search", International Journal of Cooperative Information Systems 第 4 巻第 4 号 (平成 7 年 12 月)

講演

1. 楢崎修二, 古賀慎一郎, 谷口倫一郎, 河口英二, "知的画像処理支援システム IPSSENS-II におけるデータ管理方式について", 情報処理学会九州支部大会 (昭和 63 年 3 月)

2. 吉田紀彦, 楢崎修二, "場と一体化したプロセスの概念に基づく並列協調処理モデル", 電子情報通信学会技術研究報告 CPSY 89-19(平成元年 8 月)

3. 楢崎修二, 吉田紀彦, "並列協調処理モデル Cellula の実現と評価", 日本ソフトウェア科学会第 6 回大会 (平成元年 10 月)

4. Norihiko Yoshida, Shuji Narazaki, "A Cooperation Model Composed of 'Process + Field' Amalgams", 「並列計算のモデルと応用」に関する日英ワークショップ (平成元年)

5. 楢崎修二, 堀田英一, "通信サービス記述のための知識と動作に基づく様相論理 SSL", 第 40 回情報処理学会全国大会 (平成 4 年 3 月)

6. 楢崎修二, 堀田英一, "通信サービス記述のための知識と動作に基づく様相論理 SSL", 信学技報 COMP(平成 4 年 5 月)

7. 楢崎修二, 堀田英一, "通信サービス記述のための知識と動作に基づく様相不動点論理 SSL", 情報処理学会研究会報告 PRG(平成 4 年 8 月)

8. 楢崎修二, 吉田紀彦, "大規模分散計算環境下における分散探索エージェントの通信戦略", 日本ソフトウェア科学会第 10 回大会 (平成 5 年 6 月)

9. 楢崎修二, 吉田紀彦, "大規模分散計算環境における分散探索エージェントの通信戦略", 情報処理学会研究報告 AI-93-89(平成 5 年 8 月)

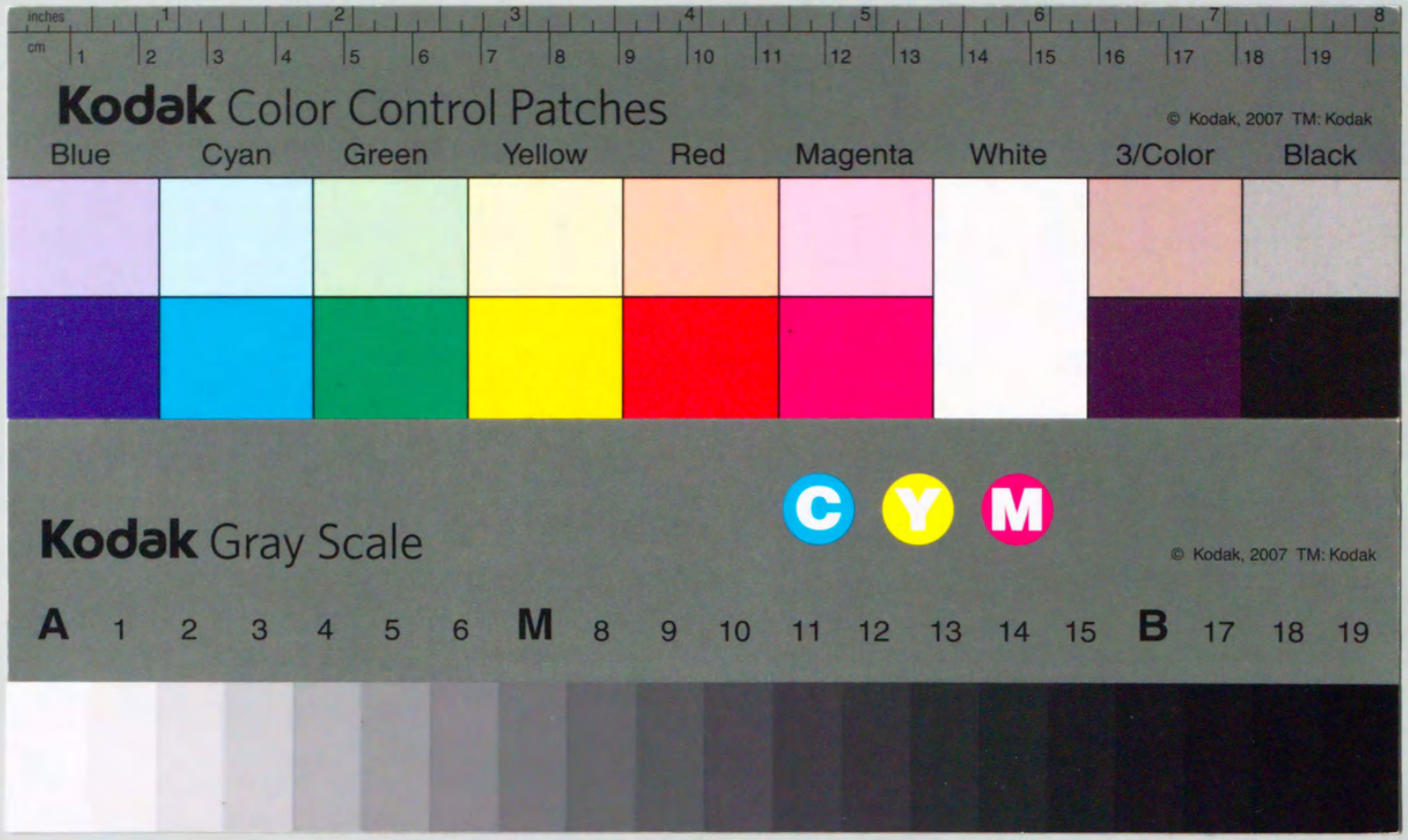
10. 楢崎修二, 吉田紀彦, "大規模分散計算環境における分散探索エージェントの通信戦略", 文部省重点領域研究「超並列原理に基づく情報処理基本体系」第 3 回シンポジウム (平成 5 年 9 月)

11. 楢崎修二, 吉田紀彦, "自己組織化エージェントによる超並列協調処理", 文部省重点領域研究「超並列原理に基づく情報処理基本体系」第4回シンポジウム (平成6年3月)

12. 山村広臣, 楢崎修二, 牛島和夫, "協調探索におけるエージェント間の通信頻度決定戦略", 電気関係学会九州支部連合大会 (平成6年9月)

13. 山崎賢治, 楢崎修二, 牛島和夫, "メタオブジェクトを用いた分散問題解決プログラムの分離記述", 1995年電子情報通信学会全国大会 (平成7年3月)

14. 山崎賢治, 楢崎修二, 牛島和夫, "メタレベル計算を用いた協調処理の実現", 情報処理学会研究報告 PRG95-82(平成7年8月)


inches
cm
Kodak Color Control Patches
© Kodak, 2007 TM: Kodak
Blue Cyan Green Yellow Red Magenta White 3/Color Black
C Y M
Kodak Gray Scale
© Kodak, 2007 TM: Kodak
A 1 2 3 4 5 6 M 8 9 10 11 12 13 14 15 B 17 18 19