TWlib – a Library for Distributed Search Applications*

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Abstract

We present TWlib, a library to support the knowledge-based distribution concept teamwork, that is intended for such search processes that use a set of facts as representation of the state and addition and removal of facts as transition between states. Teamwork has proven to be quite successful in different applications by generating synergetic effects. Teamwork employs four types of components. Experts and specialists work independently on solving the search problem. Cooperation is achieved by periodically judging the new generated facts by referees and generating a new start state out of the best facts. A supervisor controls the whole system and can adapt it to the given problem by exchanging bad experts and specialists. TWlib provides communication functions (including a secure broadcast) and control skeletons for the teamwork specific flow of control.

1 Introduction

Knowledge-based search is the basic method employed in many AI systems. Planning systems, learning systems or deduction systems, all have to deal with very large search spaces and use knowledge to find good paths through these spaces. But even the use of this additional knowledge is sometimes not enough to meet the efficiency requirements of these systems.

One obvious way to speed up search is to do it in parallel. Unfortunately, knowledge-based search requires the ability to react quickly to new possibilities that are the result of the last search step done. Therefore parallelization methods that only try to achieve a higher number of search steps per time unit do very often not combine well with the quick evaluation of and reaction to evolving possibilities. As a result, the parallel system may even be less efficient than the knowledge-based sequential one.

Approaches to combine knowledge-based systems with the possibilities of distributed computation are one of the main foci of distributed AI. But unfortunately, the efficiency of the developed systems is not the main concern of many researchers. Since the development of an efficient system in an application domain requires experiences in operating systems, DAI and the problem solving methods needed for the application, often compromises are made. Such a compromise very often is to neglect the operating system part by using either easy (and not very efficient) solutions to problems of this level or by employing development (see, for example, ARCHON [9]) and testbed (see, for example, DRESUN [2] or MACE [7]) systems for DAI applications. Although these systems offer much comfort for implementing various multi-agent systems, they have to support often quite different concepts. This results in not very efficient realizations of these concepts, again.

Researchers in the field operating/distributed systems have encountered this efficiency problem also. Their solution is to propose operating systems with only a small fixed kernel and various (specialized and efficient) extensions that serve different needs of the users of the system (see [10]). A user then chooses those extensions that optimally suit his requirements. No compromises are made.

For DAI this concept means not building a testbed for all or many multi-agent concepts a user might be interested in, but building small libraries that optimally support one (or a few very related) concept(s). In this paper we present such a library, called *TWlib*, for the *teamwork method* (see [3]), a distribution method for a certain knowledge-based search process we call *search by extension and focus*.

Search by extension and focus can be characterized as follows. The search state is represented by a set of so-called facts. Adding or changing facts are the *extensions* that produce new states. Since there are typically many extensions, the search is *focused* on parts of them by the use of guiding heuristics. Examples

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for search problems using this process are automated theorem proving and optimization problems.

It is no trivial task to find the appropriate focus heuristic to an instance of a problem. Our teamwork method takes care of this problem by employing several guiding heuristics independently in parallel on different computers. In order to achieve a cooperation between these heuristics, the search states on each computer are periodically evaluated by so-called referees. These referees also select outstanding facts of the computers. A supervisor generates then a new start search state, using the reports of the referees, which is transmitted to all computers to start a new round.

Teamwork has proven to be quite successful for search by extension and focus in different applications (see [4], [3]). The cooperation of the different heuristics results in *synergetic effects*. But implementing a teamwork based search system requires a complicated communication and control structure in order to be efficient. Our TWlib, written in C++, provides the necessary procedures and procedure skeletons to allow a potential user of teamwork to concentrate on the specific questions of the search problem, for example what heuristics to use, how to build referees and a supervisor. So there is no need to deal with implementing communication and control primitives.

2 Search by extension and focus

In literature search processes are described by *states* and *transition* rules between states. A useful classification of search processes is based on the representation of states. There are two groups of search processes. Members of the first one need explicit information about the history of the process while members of the second one do not need to represent this information explicitly.

Search processes of the first group are often based on such principles as dividing a problem into subproblems and therefore use trees or directed graphs as representations of the search state. Search processes of the second group use sets of results as representations of the state. Note that there may be processes of both groups that can be used to solve a given search problem. Our TWlib is aimed at distributing search processes of the second group. Therefore we will give in the following a formal definition of these processes.

Definition 2.1 (Search by extension and focus)
Search by extension and focus *is described by a 4-tuple* $(\mathcal{B},\Omega,\mathcal{I},S_0)$. *The set of possible facts* $\mathcal{B}$ *defines the possible states* S *of the search by* $S \in 2^{\mathcal{B}}$. Ω *is a predicate defined on* $\mathcal{B}$ *and used to describe a legal state* S *of the search by* $\Omega(s)$ *is true for all* $s \in S$. $\mathcal{I}$ *is a set of extension rules* $A \rightarrow B$, $A,B \in 2^{\mathcal{B}}$. S_0 *is called the start state of the search and has to be a legal state. We write* $S \vdash_{\mathcal{I}} S'$ *for states* S *and* S', *if there is a rule* $A \rightarrow B \in \mathcal{I}$, *such that* $A \subseteq S$ *and* $S' = (S \,/\, A) \cup B$. *A sequence* $(S_0,S_1,...,S_n)$ *with* $S_{i-1} \vdash_{\mathcal{I}} S_i$ *for* $i=1,...,n$, *is called a search derivation.*

Typically, doing search means applying a search process to an instance of the search problem. In our formal definition the search process is represented by $\mathcal{B}$ and $\mathcal{I}$, while the actual instance determines S_0 and Ω and also provides the goal of the search.

Definition 2.2 (Goal of a search)
Let $(\mathcal{B},\Omega,\mathcal{I},S_0)$ *be a search by extension and focus and* $g \in \mathcal{B}$ *with* $\Omega(g) = true$ *the* goal *of the search. A state containing* g *is called a* goal state. *The goal is* reachable, *if there is a search derivation* $(S_0,S_1,...,S_n)$ *such that* S_n *is a goal state.*

So, the main problem of a search is to find a (short) search derivation to a state that includes the goal. Since there may be many possible extensions to a given state, there has to be a function that determines which extension should be chosen next, i.e. a function providing a focus. Typically, such a focus function associates with each pair (state, extension rule) a weight that rates the extension step.

Definition 2.3 (Focus function)
Let $(\mathcal{B},\Omega,\mathcal{I},S_0)$ *be a search by extension and focus and* g *its goal. An injective function* $f: 2^{\mathcal{B}} \times \mathcal{I} \rightarrow Z$ *is called a* focus function *and the derivation* $(S_0,S_1,...,S_i,...)$ *is produced by* f, *if for the extension* $A_i \rightarrow B_i$ *that produced state* S_i *we have* $f(S_{i-1},A_i \rightarrow B_i) \leq f(S_{i-1},A \rightarrow B)$ *for all* $A \rightarrow B \in \mathcal{I}$.

If one wants to allow only legal states in a search sequence, then the focus function only has to rate pairs $(S_{i-1},A \rightarrow B)$ that produce a legal state. In practise, often the condition "injective" function is dropped and the decision between extension steps with equal f-value is made employing the FIFO-strategy. This way there are many focus functions that can be used, often too many to allow an automated decision which one to choose for a given problem instance. Another problem is that very often none of the implemented focus functions are good enough to solve a given problem instance in an acceptable time. These problems are solved by our teamwork method.

3 The teamwork method

The teamwork method is our approach to distribute search by extension and focus. A system based on teamwork has four types of components: experts, specialists, referees and a supervisor. The interaction

between these components is organized as a cycle with three phases. In the **competition phase**, also called working phase, experts and specialists work independently on their tasks. In the **judgement phase**, the first part of a *team meeting*, referees judge the work of the experts and specialists and select outstanding results and in the **cooperation phase**, the second part of a team meeting, the supervisor generates a new start state for the further search.

Experts work on solving the given problem instance by using search by extension and focus. Each expert uses a different focus function, thus generating different search sequences.

Definition 3.1 (Expert)
An expert *X is characterized by a focus function* f_X*:* $2^{\mathcal{B}} \times \mathcal{I} \rightarrow Z$*. An expert starts cycle i with start state* S_i*. During cycle i an expert may be active, i.e. running on a processor, or not. By* $\mathcal{E}xp$ *we denote the set of all experts.*

Specialists can also work on solving the problem instance, without being limited to using search by extension and focus, or they can generate data that helps controlling the search or they can combine these two tasks.

Definition 3.2 (Specialist)
A specialist *Sp is a function* f_{Sp}*:* $2^{\mathcal{B}} \rightarrow 2^{\mathcal{B}} \times$ *message-set. It starts cycle i with the set* S_i *of facts and returns a set* Res_{Sp} *of facts with* $\Omega(s) =$ *true for all* $s \in Res_{Sp}$ *and it can also return a message out of a set of messages for the supervisor. During a cycle a specialist may be active or not. By* $\mathcal{S}pec$ *we denote the set of all specialists.*

Note that a specialist can produce its set Res_{Sp} by any correct means. The set of possible messages *message-set* has to be defined by the user. Each message of *message-set* has to be interpreted by the supervisor.

Referees have two tasks: computing a measure of success for experts and some specialists and selecting outstanding results of experts and specialists. The results of both tasks are passed on to the supervisor. A referee of a specialist also reports the message of the specialist (if there is any).

Definition 3.3 (Referee)
A referee *R consists of two functions*

$meas_R$*:* $(2^{\mathcal{B}})^* \rightarrow Z$ *and*

$selres_R$*:* $2^{\mathcal{B}} \rightarrow \mathcal{B}^{\leq k}$,

where $(2^B)^*$ *is a sequence of states and k the maximal number of results that may be selected by the referee. By* $\mathcal{R}ef$ *we denote the set of all referees.*

If a referee judges the success of an expert then it uses the whole search sequence produced by it as basis for its judgement. Since specialists can use totally different representations for their search states, the referee can only use the set Res_{Sp}. This is also the set $selres_R$ chooses from, while a referee of an expert uses its last search state as input for $selres_R$.

The supervisor achieves the cooperation of experts and specialists by generating a new start state for the next cycle out of their results. But it also compares the success of the experts and specialists and selects the members of the team of the next cycle using the measures of success of the experts and specialists in prior cycles and further information provided by a long-term memory (see [5]). Also the messages of the specialists are used. As third task the supervisor determines the length of the next cycle using the same information.

Definition 3.4 (Supervisor)
The supervisor *computes after a cycle i the following three functions:*

$Comp$*:* $(2^{\mathcal{B}} \times \mathcal{B}^k \times \mathbb{Z})^n \rightarrow 2^{\mathcal{B}}$

Sel_i*:* $(\mathcal{E}xp \cup \mathcal{S}pec) \times \mathcal{R}ef \rightarrow \{0,1\}$

$Time_i$*:* $2^{\mathcal{B}} \times ((\mathcal{E}xp \cup \mathcal{S}pec) \times \mathcal{R}ef)^n \rightarrow N$

where n is the number of available processors.

While the function $Comp$ that computes the new start state remains the same throughout a whole distributed search run –it simply uses the state produced by the expert with the best measure of success and adds the selected results of the other experts and the specialists to generate the start state– the functions Sel and $Time$ change from cycle to cycle, indicated by index i, because they have to take the results of the prior cycles and the messages of the specialists into account. Since there are only n processors available, we demand $\sum_{x \in \mathcal{E}xp \cup \mathcal{S}pec} Sel_i(x, \_) = n$, so that only n experts and specialists (with their referees) are active in each cycle.

Implementing the control cycle and the communication between the components requires more than knowledge about the search problem one wants to solve. It is possible to avoid some interprocessor communication by allowing components of different type to share a processor. Since an expert or specialist, a referee or the supervisor never are active during the same time, one can implement them as one process having different modi (or an agent having different roles).

So, at the beginning of a distributed run, the process on one processor is in supervisor mode, receiving the problem instance. After generating a search state, the process sends this state to all other processors

whose processes are in expert or specialist mode. Until the next team meeting the work of the supervisor is done and this process changes to expert mode.

When the end of a working phase is reached, each processor changes into referee mode. This way the referees can access all data of their experts/specialists without expensive communication. After the judgement phase the process that was in supervisor mode at the end of the last meeting changes back into supervisor mode and receives the measures of success of all experts and specialists (function $meas_r$). After the best expert is determined, its process changes to supervisor mode. This new supervisor receives the full reports of the referees. The selected results of the other experts and the specialists can be integrated directly into the actual search state of the process in supervisor mode. After determining the members of the team in the next cycle the new start state is transmitted to the other processes and a new cycle begins.

By carefully choosing point-to-point connections between processors or broadcasting to all processors (the later when transmitting the new start state), one is able to achieve communication and control without much overhead. Then the following synergetic effects occur, that allow a team to be much more effective than single experts that employ only one focus function.

- A good but not quite good enough expert can receive missing results from other experts. This effect is based on the cooperation aspect of teamwork.
- An expert may be able to generate a good search state, but then can not continue towards the goal. Another expert can, starting with this good search state, continue towards the goal. This change of focus functions produces search sequences that are much better than all sequences produced by one expert alone and it is based on the competition aspect of teamwork.

While a potential user of teamwork still has to write procedures for the components that allow for synergetic effects, our TWlib provides the necessary communication and control primitives and also skeletons (with respect to these primitives) for the components. Please note that the communication structure of teamwork has requirements on the system software level that are typically neither directly provided by operating systems nor by development packages for distributed systems as for example PVM (see [8]). Such a requirement is, for example, a secure broadcast.

4 The TWlib

In order to allow potential users of teamwork to get rid of the system software part of an implementation of a teamwork based system we developed a C++ class library called **TWlib**. This library offers a set of classes with associated methods, some of which are only skeletons that have to be extended according to the search problem that has to be solved. We have chosen C++ in order to provide an object-oriented view without much loss of efficiency and also to use a widely known programming language. The first version of TWlib is based on UNIX (Sun OS 4.1.4) and the TCP/IP protocol suite for interprocess communication.

In the following we will begin our presentation of TWlib with some remarks about the class hierarchy and dependencies. Then we will characterize the tasks an implementer using TWlib has to do which also characterizes the tasks TWlib takes care of. Then we take a deeper look at the main class of TWlib, class teamworkApplication.

4.1 The class hierarchy and dependencies of TWlib

The main purpose of TWlib is to support the necessary communication between the objects involved in a teamwork application and their internal scheduling tasks. These objects can be located on different computers and therefore, object communication includes network communication as well. In addition, the teamwork specific data and control flow is provided by skeletons of methods which have to be expanded by the user. Error handling and logging of events are also supported. These tasks together lead to the class hierarchy and dependencies that are depicted in Figure 1.

An implementer employing TWlib will only have to deal with classes Xpert, Specialist, Referee and teamworkApplication which form the *application layer* of TWlib.

The other classes form the *core layer* and the *system layer* which encapsulates the underlying operating system. Class processGroup is an administrative class holding information about the environment (e.g. the other processes) of a process. Another administrative class is the class CEPSet which controls all the connections between a process and the other processes. These connections are used to transmit asynchronous events, point-to-point messages like referee reports and broadcast messages like the new start state of the search. Please note that we implemented a secure broadcast (no simulation) that uses point-to-point messages only for acknowledgments and missing information. All this functionality is provided by the

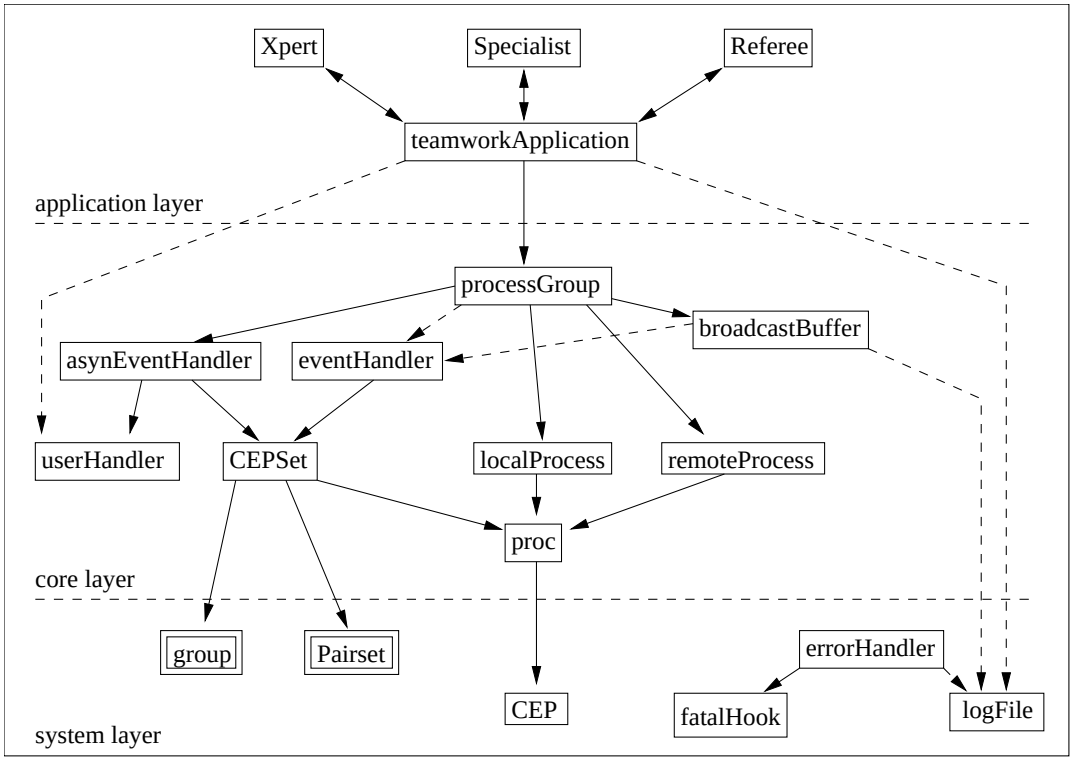

Figure 1: Figure 1: class hierarchy and dependencies of TWlib

classes CEP (communication end point) and broadcastBuffer.

Classes group and Pairset provide data structures that are used for process control and finally class errorHandler contains TWlib's error I/O and a hook for a user function to be called on a fatal error.

4.2 Tasks of an implementer using TWlib

Since TWlib is intended as basis for many very different applications, all functions and program segments that deal directly with the application or its data structures have to be provided by the implementer. More precisely, an implementer has the following tasks:

- Providing code for the components and the data structures they use.
- Providing initial data about the computers to use and announcing all components that can be used to the system in a predefined format.
- Implementing send and receive functions for referee reports and search states. The library offers transfer routines for character streams, so that converting application data formats into character streams (and backwards) is sufficient.
- Providing the function that chooses the new supervisor during a team meeting.
- Providing the supervisor functions Comp, Sel_i and Time_i. The resulting schedule for the next working phase must be given to the system in a predefined format.

The TWlib takes care of all other tasks. The most important of these tasks are:

- providing administrative data structures for experts, specialists and referees
- process management
- efficient communication via
  - secure broadcast
  - simulated broadcast (short messages only)
  - point-to-point connections

In addition, the classes of the application level include skeletons that simply can be completed for:

- initializing the whole system
- experts, specialists and referees

- the main loop of a process including the course of events of a team meeting
- error handling and normal and abnormal program termination

4.3 Class teamworkApplication

The classes of the application level of TWlib map the theoretical concepts of section 3 to an actual implementation. The flow of control in a teamwork-based system consists of an *Initialization* phase and a *Work/Meeting* loop. The loop can only be left by calling an exception (an asynchronous event). If no error occurs, the exception causes the *End* sequence to be executed.

The whole flow of control is implemented in class teamworkApplication. An implementer using TWlib should derive his own classes (e. g. UserXpert, UserSpecialist, UserReferee and UserteamworkApplication) from the respective base classes of TWlib and override the methods which deal with the specific application area. In the following we will describe the class teamworkApplication by tracing the execution of the method `main` of this class. An excerpt of this method is depicted in Figure 2. When the teamwork root process is started, a (User)teamworkApplication object should be created and control should be passed to the new object's `main` method instantly.

```
void teamworkApplication::main( int argc, char** argv ) {
                    :
  if( !thisProcess->isInitial( argc, argv )){
      // we are not the teamwork root process...
      role = XP;
      initXpert( argc, argv );
      initUserCode();
      receiveInitialSystem();
      while( true ){
          work();
          meeting();
      };
  }
  else{
      // we are the teamwork root process...
      role = SV;
      initSupervisor( argc, argv, conf_files );
      initUserCode();
      sendInitialSystem();
      while( true ){
          work();
          meeting();
      }
  }
}
```

Figure 2: Extract of method `main`

Note that this method is used by all processes on the different computers which means, that each process has exactly one object of class teamworkApplication. Since this class contains the code for all different roles (experts, referees, supervisor, etc.) some distinction which portion of the code should be executed in a particular situation must be made in method `main` and subsequent methods.

4.3.1 The Initialization

The initialization usually begins by reading information about the configuration of the system from so-called configuration files. This is normally the first action of method `initSupervisor` of the supervisor process (see Figure 2). Please note, that the startup sequence for the remote processes has some user hooks to customize the start parameters for every single host. For more information we refer to the documentation that is included in the distribution package of TWlib. Using the read in information, the expert processes are started on the remote machines and the communication network between all processes of a teamwork application is set up.

After the initialization, method `initUserCode`, which should be overridden by the implementer, allows to transfer information about the components into the internal database of the teamworkApplication object of each process. The source of this information can be the configuration files read in during the system initialization. Since a teamworkApplication object includes the administration of all experts, specialists and referees, these components have to be announced to the object. The class teamworkApplication provides methods `announceX` (where X stands for Xpert, Specialist or Referee) for this task. The result of these methods is always a unique id which is used by the teamworkApplication object to refer to this component. The announcements should be made to each teamworkApplication object on the different host computers in the same order to guarantee that each component has the same id in all processes.

In order to compose a starting team (for a working phase) an initial schedule (i. e. an Xpert/Specialist and a referee assignment to each process), must be composed. An individual assignment is made by calling method `assignX` with the id of the component and the id of the process it should be assigned. Before a working phase only one referee and either an expert or a specialist may be assigned to a process. The objects associated with the respective ids will be called when the `work` or `assess` methods of the teamworkApplication objects are invoked. Since typically the next team is formed by the supervisor TWlib provides methods, called `sendAssignment` and `receiveAssignment`, to inform the other processes about their next schedule.

Finally, the description of the actual search problem to solve has to be sent to all remote processes (methods `sendInitialSystem`, resp. `receiveInitialSystem`). This problem is also read from a configuration file. In order to demonstrate the methods for communication provided by the classes of the system level, we included the code of these two

methods from an example user application class sampleApp in Figure 3. The object pg is of class processGroup.

```
void sampleApp::sendInitialSystem( void ) {
  //-------------------------------------------------------
  // ALL       = virtual broadcast for short messages
  // BROADCAST = physical broadcast for lots of data
  //-------------------------------------------------------
  pg->write( ALL, (void*)&goal, sizeof( unsigned long ) );
  pg->write( ALL, (void*)&eps_env, sizeof( unsigned long ) );
  pg->write( ALL, (void*)&maxIndex, sizeof( int ));
  for( int i = 0; i < maxIndex; i++ ){
      if( pg->write( BROADCAST, (void*)&(data[i]),
                     sizeof( unsigned long )) < 0 ){
          ERR.fatalLog( __FILE__, "write error, exiting..." );
      }
  }
  pg->flush();
}

void sampleApp::receiveInitialSystem( void ) {
  pg->read( supervisor, (void*)&goal, sizeof( unsigned long ));
  pg->read( supervisor, (void*)&env, sizeof( unsigned long ));
  pg->read( supervisor, (void*)&size, sizeof( int ));
  for( int i = 0; i < size; i++ ){
      if( pg->read( BROADCAST, (void*)&(data[i]),
                    sizeof( unsigned long )) < 0 ){
          ERR.fatalLog( __FILE__, "read error, exiting..." );
      }
  }
}
```

Figure 3: Examples for methods sendInitialSystem and receiveInitialSystem

4.3.2 The main loop

In the loop of method **main** one can observe the two main phases of a teamwork application : the working phase and the team meeting. As already stated, invoking method **work** calls the expert/specialist that is assigned to a process for the actual working phase. Only the actual supervisor has to invoke an additional method: **setWorkingParams**. This method installs a timer object which interrupts all processes after the time given by the supervisor (see Figure 4).

```
void teamworkApplication::work( void ) {
  if( role == sv){
      setWorkingParams();
  };
  Xperts->getByFirst( xp )->work();
}
```

Figure 4: Method work

Then method **meeting** is invoked (see Figure 5). Method **assess** calls the referee that is assigned to a process. The following methods form a skeleton that has to be expanded by overriding the respective methods according to the intended application. The methods **sendShortReport** and **receiveShortReport** transmit the results of the $meas_R$-function of the referees. Note that both methods have no arguments. Instead the implementer has to put the results of the referee-functions into memory areas which are read by these methods. Figure 6 shows the code for these two methods.

```
void teamworkApplication::meeting( void ) {
  assess();
  if( role == sv){
      receiveShortReports();
      newSupervisor = chooseNewSupervisor();
  }
  else{
      sendShortReport();
      newSupervisor = getNewSupervisor();
  }
  if( newSupervisor == thisId ){
      receiveFullReports();
      integrateResults();
      changeTeamSetup();
      sendNewSystem();
  }
  else{
      sendFullReport();
      changeTeamSetup();
      receiveNewSystem();
  }
}
```

Figure 5: Method meeting

```
void sampleApp::sendShortReport( void ) {
  pg->write( supervisor, (void*)&rep->assess, sizeof( double ));
}

void sampleApp::receiveShortReports( void ) {
  for( int i = 0; i < mem.groupSize(); i++ ){
      pg->read( &mem, &from, (void*)&assess, sizeof( double ));
      report = new Report;
      report->from = from;
      report->assessment = assessment;
      Reports->append( report );
  }
}
```

Figure 6: Examples for methods sendShortReport and receiveShortReports

The method **chooseNewSupervisor** has to select the best expert and its processor and has to transfer this information to all other processes (**getNewSupervisor**) Then the referees of the experts/specialists send their full reports, i.e. the results of their $selres_R$-function, (**sendFullReport**) to the new supervisor (**receiveFullReports**) that integrates these results (**integrateResults** realizes the function Comp). The method **changeTeamSetup** is responsible for selecting the next team (function Sel_i) and assigning an expert/specialist and referee to each processor. Then the supervisor transmits the new start state (**sendNewSystem**) to all other experts/specialists (**receiveNewSystem**).

4.3.3 The End Sequence

The last phase of a teamwork application is entered when an expert or specialist has found the goal of the search. This expert/specialist invokes the method **goalReached** which issues an asynchronous event **GOAL_REACHED** causing all processes to call method **cleanup** of their teamworkApplication object. That method can use the predicate **reachedGoal** to test whether the local process has found the goal. An implementer can add the necessary presentation functions for the user of his system to method **cleanup**. The last operation of **cleanup** is to terminate its host process.

5 The TWlib in use

The main goal of the TWlib is to take the system software part away from an implementer using the teamwork paradigm. The implementer gets some guidance how to structure his system and where to make his application dependent extensions through the method skeletons provided by TWlib. This should lead to a substantial gain with respect to the time needed for developing and implementing a teamwork based system.

Since there are many search problems that can be solved using search by extension and focus, we can not provide experiences for all possible applications here; but we can compare our experiments in implementing teamwork based systems before we had TWlib and after. We have developed and implemented three teamwork based systems, so far: the DISCOUNT system ([1]), the DOTT system for solving the traveling salesman problem ([3]) and the DiCoDe system, a theorem prover based on Condensed Detachment.

For implementing the first version of DISCOUNT we needed 1.5 man years starting with an already implemented unfailing completion procedure This first version did not include broadcasting abilities. Adding these abilities took another 0.5 man years.

For implementing DOTT we needed 1.5 man years, again. But in this case we did not have the code for experts already available. Although we could reuse large parts of the code for broadcasting from DISCOUNT the stated 1.5 man years resulted in a system with only one type of referees and a very crude implementation of the supervisor.

The implementation of DiCoDe, based on an already implemented sequential system CoDe (see [6]) and using the TWlib, took only 0.5 man years (with a new implementer). In fact, in DiCoDe also two small variations of the teamwork method can be used that were obtained by simply altering the method `meeting` of the TWlib. Although one might argue that DiCoDe as a theorem prover can profit much more from the experiences with DISCOUNT than DOTT, nevertheless the 0.5 man years development time led to a system that already includes more referees and a better supervisor than the first version of DISCOUNT. Obviously, the TWlib significantly reduced the implementation time.

We are currently using the TWlib in a reimplementation of DISCOUNT and for teamwork based distributed systems employing genetic algorithms (and trying to achieve cooperation with more conventional search paradigms).

Although the TWlib is already successfully used in a system we still see our current version as only a first beta version. Therefore we have chosen to distribute TWlib by request (e-mail to one of the authors) and not via an anonymous ftp-side. The distribution package of TWlib contains the library, documentation in form of a postscript-file and as a directory of html-pages, and a dummy application. The problem solved by this dummy application is quite silly, but the application demonstrates all necessary steps an implementer using TWlib has to do.

6 Conclusion and Future Work

With TWlib we presented a library to support distributed search applications that are based on the teamwork method. TWlib provides communication functions and control skeletons in order to allow an implementer to concentrate on the specific problems of the intended application. Also some data structures for administrative purposes are included in TWlib.

A high priority on our future schedule has the porting of the TWlib on other UNIX-like operating systems in order to use workstation clusters with heterogeneous operating systems. Future conceptual work centers on extending the TWlib to also include a graphical user interface. Such an interface has proven to be very useful in developing more and better components for our DISCOUNT system.

Finally, we want to use our experiences with the TWlib to provide similar libraries for other distribution concepts for search processes. Again, the main goal has to be to provide both an optimal efficiency and an easy use by implementers.

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