On the Implementation of the Opus Coordination Language*

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Abstract

Opus is a new programming language designed to assist in coordinating the execution of multiple, independent program modules. With the help of Opus coarse grained task parallelism between data parallel modules can be expressed in a clean and structured way. In this paper we address the problems of how to build a compilation and runtime support system that can efficiently implement the Opus constructs. Our design considers the often-conflicting goals of efficiency and modular construction through software re-use. In particular, we present the system requirements for an efficient Opus implementation, the Opus runtime system and describe how they work together to provide the underlying services that the Opus compiler needs for a broad class of machines.

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1 Introduction

Data parallel languages, such as High Performance Fortran (HPF) [22], have been successfully applied to a wide range of numerical applications. For single programs, significant parallelism can be achieved using high-level constructs. However, many advanced scientific and engineering applications are multidisciplinary and heterogeneous in nature, requiring several independent programs working together to generate a solution. Such applications do not fit well into the data parallel paradigm, since there are no facilities for controlling the interaction between multiple, independent program units. The Opus coordination language [7, 6] was recently designed to fill this gap.

Opus defines language extensions to HPF that support the coordination of data parallel tasks. In doing so, Opus introduces coarse-grained *task parallelism* on top of an existing data parallel model, where each *task* is represented by an independent program module. Opus also introduces a mechanism to control the coupling of multiple programs into complex multidisciplinary codes. To achieve these goals Opus provides the following set of features:

- encapsulation of separate programs into modules in a way that respects their separate name spaces;
- coupling between modules at a high language level, as opposed to using explicit message-passing constructs throughout the code;
- task-level parallelism between modules and data parallelism within each module; and
- flexible and general synchronization mechanisms that allow the programmer maximal freedom in exploiting task-level parallelism.

In a previous paper [7], we presented the syntax and semantics of the Opus language. In this paper, we describe the design of a system that efficiently implements the Opus constructs. We provide an overview of the whole system, ranging from the low level virtual machine up to the high level compiler component. Our system design has to face several requirements, including efficient support for data parallelism, an efficient implementation of the coordination mechanisms of the language, the possibility to extend and modify the language, and portability to a broad class of machines.

Apart from describing our present system design we discuss design alternatives, together with their advantages and disadvantages, and motivate why we came up with our design. Our approach deals with the often-conflicting goals of efficiency and modular construction through software re-use. Software re-use is of invaluable importance when designing a highly complex system. For example, we utilize an existing HPF compilation system (the *Vienna Fortran Compiler VFC* [3]) for the data parallel portion of our work. We also utilize existing libraries that provide useful communication and threading abstractions, but avoid larger runtime packages such as Nexus [12] and Chant [18] for reasons that we will explain later in more detail.

Finally, although our system has been specifically designed to meet the requirements of the Opus language, we believe that the design decisions described in this paper can be applied in a more general context. In particular, we show that the usage of a multithreaded virtual machine is advantageous for modeling complex asynchronously interacting tasks. Moreover, we found that

hybrid systems where a compiler and a runtime system work together can provide more efficient solutions than systems that focus on sophisticated runtime support.

The remainder of this paper is organized as follows: After a short introduction to the Opus Language in Section 2 and the Opus Execution Model in Section 3 we present our detailed system design in Section 4. Possible design alternatives and related work are discussed in Section 5. In Section 6 we validate the effectiveness of our approach with some preliminary results and end in Section 7 with some concluding remarks and a discussion of future work.

2 The Opus Language

Opus introduces a small set of extensions to HPF [22] designed to coordinate an efficient parallel execution of multiple, independent program modules. At the heart of these extensions is an abstract data type called a ShareD Abstraction, or *SDA*, whose purpose is to provide a means for encapsulation of data and methods (procedures) which act on this data. Syntactically, Opus borrows heavily from Fortran 90 [25] in the definition and use of SDAs. SDAs may exploit data parallelism in that the internal data of SDAs as well as the data of SDA methods may be distributed. The full power of HPF is exploited for specifying data parallelism.

Viewed as an abstract data type, an *SDA type* specifies an object structure, containing data and the *methods* (procedures) which manipulate this data. By *creating* an instance of an SDA type an *SDA object* (or simply SDA) is created. At creation of an SDA, the resources on which it will execute are allocated, and all SDA data is allocated and initialized in order to establish a well-defined initial state. During its *lifetime*, which is the time between its creation and its *termination*, an SDA can be accessed (a method of an SDA can be invoked) from within a program via *SDA variables*.

An SDA method can be invoked *synchronously*, where the caller is blocked until control returns, or *asynchronously*, where the caller does not have to wait for the completion of the method. Explicit synchronization is possible via an *event* variable that can be associated with an asynchronous method invocation. More specifically, an SDA may *test* (or poll) an event in a non-blocking fashion, thus getting information about a method's status without having to wait for its completion, or it may *wait* until a method has finished its execution. No two methods of an SDA are allowed to execute in parallel; thus each method has *exclusive access* to the data of the SDA. A method may have an associated *condition clause*, specifying a logical expression, which guards the method's activation.

In Figure 1 we illustrate the usage of Opus with the standard producer/consumer problem. In this example a set of producers and consumers operate independently, communicating and synchronizing each other via a bounded FIFO buffer. Note, that this example exploits only the task parallel features of Opus and does not make use of data parallelism.

3 The Opus Execution Model

In order to provide a better understanding of the implementation issues discussed in the following section we sketch the Opus execution model below, taking the above producer/consumer problem

```
program producer_consumer

  sda type buffer_type(size)
    integer :: size
    real, private :: fifo(0:size-1)
    integer, private :: count = 0
    integer, private :: px = 0
    integer, private :: cx = 0
  contains
   subroutine put(x) when (count .lt. size)
      real, intent(in) :: x
      fifo(px) = x
      px = mod(px+1,size)
      count = count+1
    end subroutine put

    subroutine get(x) when (count .gt. 0)
      real, intent(out) :: x
      x = fifo(cx)
      cx = mod(cx+1,size)
      count = count-1
    end subroutine get
  end buffer_type
```

```
sda type producer_type
  contains
  subroutine produce(b)
    sda(buffer_type) b
    real a
    do
      a = ... ! produce a
      call b%put(a)
    end do
  end subroutine produce
end producer_type

sda type consumer_type
  contains
  subroutine consume(b)
    sda (buffer_type) b
    real a
    do
      call b%get(a)
       ... = ... a ... ! consume a
    end do
  end subroutine consume
end consumer_type
```

```
! main program
  integer,parameter :: np=5
  integer,parameter :: nc=5
  integer,parameter :: buffersize=10
  sda(buffer_type) buffer
  sda(consumer_type) consumer(nc)
  sda(producer_type) producer(np)
  call buffer%create(buffersize)
  do i = 1,nc
    call consumer(i)%create
  end do
  do i = 1,np
    call producer(i)%create
  end do
  do i = 1,np
    spawn producer(i)%produce(buffer)
  end do
  do i = 1,nc
    spawn consumer(i)%consume(buffer)
  end do
end program producer_consumer
```

Figure 1: Producer/Consumer Problem with Opus

as a practical example.

During its execution an Opus program consists of a *main procedure* and a set of *SDA objects* which are created and destroyed dynamically during the lifetime of the main procedure. In the following, when it is clear from the context, we will simply refer to *SDAs* instead of *SDA objects*. Every SDA (and the main procedure as well) executes asynchronously in a unique address space called *SDA Address SPace (SASP)*, containing the data and the executable code of an SDA. Each SASP is mapped to a set of physical computational units called *nodes*, where a node can e.g. be a workstation or a processor in a multi-processor machine. The distribution of a SASP across more than one node, for example the processors of a distributed-memory machine or a network of workstations, allows the exploitation of data parallelism. Distributed SASPs give raise to some difficult issues such as proper synchronization of method executions and data exchange as will be discussed in Section 4.2.1. A more detailed treatment of issues relating to the combination of task and data parallelism can be found in [1]. In order to exploit the available resources efficiently, multiple SASPs may reside on a node.

The execution of an Opus program starts by executing the main procedure, so that we begin with a single (possibly distributed) SASP. When new SDAs are created, we allocate new SASPs on specific sets of nodes. After an SDA has been created, it runs asynchronously and in parallel with all other SDAs in the program. There is a parent/child relationship between SDAs; a parent SDA can only terminate if all of its children have finished their execution. SDAs can communicate with each other via *method invocation (MI)*.

In our producer/consumer example the *main procedure* creates *np*+*nc*+1 SASPs (1 *buffer*, *np* *producers*, and *nc consumers*). The *main procedure* issues an asynchronous MI to every *producer* (*consumer*), causing the execution of the *produce* (*consume*) method. During the execution of these methods synchronous MIs to the *buffer* are issued, resulting in the execution of the *put* or *get* method, respectively. The *buffer* executes these methods conditionally, thus ensuring a correct program behavior.

During its lifetime an SDA can be in one of three different *execution states: ready*, *executing*, or *waiting*. After its creation an SDA is *ready* for method invocations. All incoming MIs

are buffered and, depending on the associated "when-conditions", one of them is chosen to be *executed*. During the execution of a method in response to an MI, an SDA may communicate with other SDAs via MIs, it may create additional SDAs, or it may be *waiting* on the return of MIs. After having finished its current execution, the SDA either executes another method if an MI with satisfied "when-condition" is available or switches back to the *ready* state. Note that even if an SDA is in the *ready* state there may well be buffered MIs with a not satisfied "when-condition".

All SDAs of our example program are initially ready. After the *producers* and *consumers* have received their MIs they switch to the executing state and start executing the respective procedure. The *main* procedure switches to the waiting state after all MIs have been issued. The *producers* and *consumers* switch to waiting after they have issued their synchronous MIs to the *buffer*; after the return of the MIs they resume their execution. Analogously, the *buffer* switches between ready and executing. It can never be waiting since it does not issue any MIs.

An Opus implementation has to provide an efficient mapping of SASPs to nodes as well as efficient means of interaction between SDAs. Moreover, it has to ensure that an SDA is capable of receiving and buffering new MIs independently of its state. Buffering MIs should be accomplished without unnecessary copying of MI arguments, which can include large segments of data. We provide a detailed discussion of how an implementation of Opus can fulfill these requirements in the following section.

4 An Implementation of Opus

In this section we discuss in detail how an Opus program is compiled and describe the components of the Opus system. Apart from having an efficient and portable implementation one of the main design goals was the integration with an existing HPF compilation system (the *Vienna Fortran Compiler VFC* [3]), so that we do not have to re-implement any of the HPF compiler work.

4.1 Introduction

The transformation of an Opus source code into an executable program is a 3-stage process as can be seen in Figure 2:

- The Opus Compiler (*OC*) transforms the code into blocks of HPF code with calls to the Opus Runtime System (*ORS*). This transformation process uses *compilation templates* which specify code structures common to every Opus application (cf. Section 4.3).
- This code is further processed by VFC which produces F90 code with calls to the VFC runtime system.
- The resulting F90 code is eventually compiled with a F90 compiler and linked with both the VFC runtime system and ORS.

While in the initial implementation of Opus [19] a fairly sophisticated runtime system was used, in our present system design the role of the runtime system is reduced to basic communication

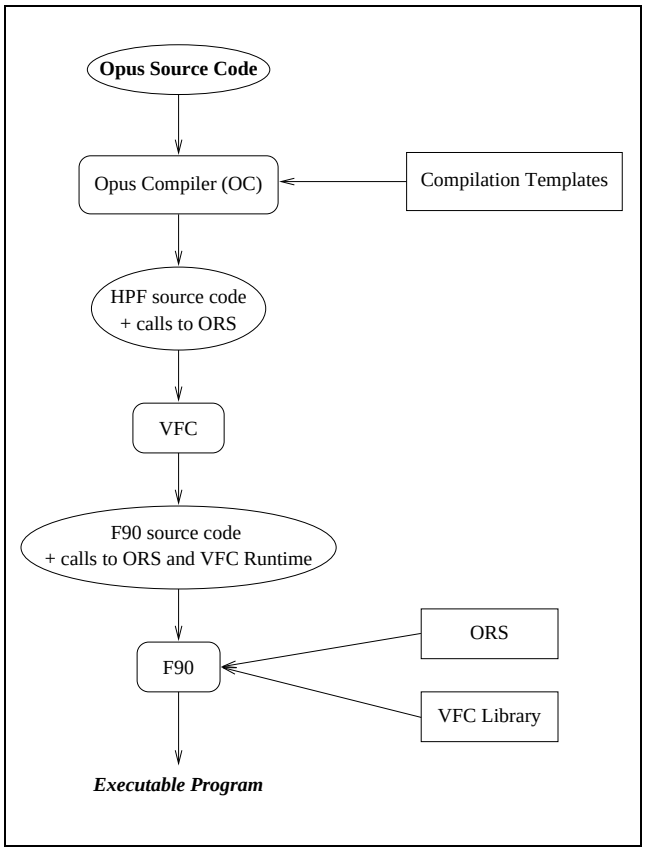


Figure 2: The Opus Compilation Process

and SDA management tasks (cf. Section 4.2), while the Opus compiler implements most of the SDA semantics such as scheduling of MIs and efficient argument handling. In particular, ORS integrates and abstracts lower level system components for both, SASP mapping and interaction (cf. Figure 3). We require communication mechanisms that do not assume a shared memory model for realizing SDA interaction. For an efficient mapping of SASPs we need to facilitate mappings of multiple SASPs to the same node, in order to exploit locality between SDAs. Such a mapping could be realized on Unix-based systems by mapping each SASP to a process, but this approach suffers from two major drawbacks: the inability to control scheduling and the costly context switching overheads (cf. [19]). In light of the problems with using a process-based model, we have elected to use a *multithreading* model. However, some support for a process-based model is necessary for platforms which do not allow multithreading as will be discussed in Section 4.4.

In our current design we make use of low-level packages for both communication and multithreading. The actual modules used vary from system to system, but include systems like MPI [27], TCP/IP [23], and POSIX threads [24]. These low level components can be seen as part of the virtual machine on top of which an Opus application will be executed.

We now provide a detailed discussion of the Opus system design, in particular of the Opus Runtime System (*ORS*) and the Opus Compiler (*OC*).

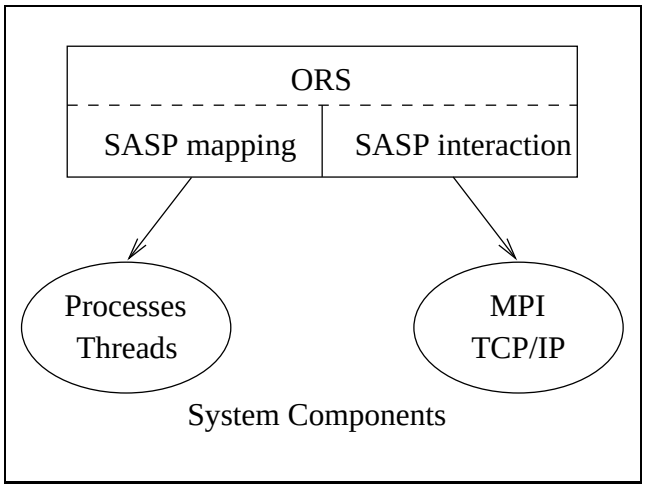


Figure 3: The Opus Runtime System and its Supporting System Components

4.2 The Opus Runtime System

The Opus Runtime System (ORS) implements the low-level runtime support that is utilized by every Opus application. Specifically, ORS exploits the functionalities provided by the underlying systems components (cf. Figure 3) and provides runtime routines for SDA management, including initialization, finalization, and MI handling.

Due to the conditional execution of methods it is necessary to buffer MIs on the callee side until the method is eventually ready for execution. This buffering is a critical task since MIs may be accompanied by large amounts of data being passed as input arguments to the method. The actual implementation of MI-buffers uses two FIFO queues called *MI-queues* in which MIs are buffered in the form of *execution records* that contain the runtime representation of an MI. This includes information about the caller and the callee, the method that is to be executed, and a set of marshaled arguments.

More specifically, ORS provides one MI-queue for buffering incoming MIs (the *inqueue*) and one for keeping track of issued MIs (the *outqueue*). The inqueue maintains an additional pointer to the so-called "current" record which is the record that should be processed next. Initially, the "current" record is the oldest one in the queue. After each unsuccessful test of a "when-condition" the pointer is redirected to the subsequent record in the list. The pointer is reset to the oldest record in the list each time a method has been successfully executed.

Figure 4 shows the type declaration (using F90 syntax) of an execution record, where the derived type `ors_sda_handle` is the runtime representation of SDAs and the type `ors_generic_type` is a compiler generated abstraction of the method arguments; apart from these pointers the execution record holds a unique id, the id of the method to be executed, the type of the execution (synchronous or asynchronous) and a logical flag which provides information about the execution progress. The ORS implementation takes care that the management of input data does not involve additional data copying, hence an execution record has only a pointer to the method arguments.

The ORS also supports argument marshaling that is necessary for proper MI execution. The

```
TYPE ors_execution_rec
   INTEGER :: id, method_id, execution_type
   LOGICAL :: finished
   TYPE(ors_sda_handle), POINTER :: caller
   TYPE(ors_sda_handle), POINTER :: callee
   TYPE(ors_generic_type), POINTER :: arguments
END TYPE ors_execution_rec
```

Figure 4: The Execution Record

complex nature of SDA methods and the fact that the internal data structures can be distributed over multiple nodes makes argument marshaling a non-trivial task that may involve data redistribution. However, we do make use of existing redistribution algorithms or libraries [28, 5, 8]. In implementing ORS, we were careful to avoid the underlying message passing system when communicating between two SASPs co-located on the same node, so that direct memory copies can be done.

Apart from basic MI support, ORS also facilitates MI based SDA synchronization like the event mechanism described in Section 2. It also provides a higher-level interface to the underlying system components (e.g. creating a new thread or synchronizing threads via mutexes and condition variables), so that these packages can be easily exchanged without affecting ORS or the compiler.

We now provide a more detailed discussion on the implementation of ORS: Figure 5 shows the interface of the main ORS routines. The use of these routines can be seen in the following section where we discuss the Opus Compiler and its compilation templates. We omit the presentation of communication and thread routines since those are quite simple wrappers around the low level routines. It is worth noting that our actual implementation of ORS is done in F90 which, among others, facilitates the integration with existing HPF-runtime systems as will be discussed in more detail in Section 5.

- `ors_initialize_sda(iq,oq)`: The initialization routine of an SDA. It allocates the SASP, including the *inqueue* `iq` and the *outqueue* `oq`.
- `ors_terminate_sda(oq)`: This routine is invoked on the termination of an SDA and ensures correct behavior on termination. It is necessary to wait on the return of all outstanding MIs (which can be accessed via the outqueue `oq`), and a termination signal is sent to all children of the SDA. The routine has to wait until all of the SDA children have terminated in turn. After that it is safe to delete the SASP and to return.
- `ors_get_rec(rec, queue) result(return_rec)`: A pointer to an execution record of the MI-queue `queue` is returned. In case the optional argument `rec` is not provided the current record is returned. If `rec` is available a pointer to the matching record in the queue is returned. This is e.g. needed when the execution progress of an MI is queried by the intrinsic "wait" or "test" procedure.
- `ors_insert_rec(rec, queue)`: A new record is inserted into the queue.

```
ors_initialize_sda(iq,oq)  [TYPE(ors_mi_queue) iq, oq]
ors_terminate_sda(oq)      [TYPE(ors_mi_queue) oq]

ors_get_rec(rec, queue) result(return_rec)
                           [TYPE(ors_execution_rec), optional :: rec
                            TYPE(ors_execution_rec), pointer :: return_rec
                            TYPE(ors_mi_queue) queue]
ors_insert_rec(rec, queue) [TYPE(ors_execution_rec) rec
                            TYPE(ors_mi_queue) queue]
ors_delete_rec(rec, queue) [TYPE(ors_execution_rec) rec
                            TYPE(ors_mi_queue) queue]

ors_new_event(e,r)         [TYPE(ors_event) e; TYPE(ors_execution_rec) r]
ors_test(e,s) result(finished)
                           [LOGICAL finished; TYPE(ors_event) e
                            TYPE(ors_sda_handle) s]
ors_wait(e,s)              [TYPE(ors_event) e; TYPE(ors_sda_handle) s]
ors_handle_inquiry(r,c,a)  [TYPE(ors_execution_rec) r,c; INTEGER a]

ors_handle_return(r)       [TYPE(ors_execution_rec) r]
```

Figure 5: Main ORS Routines

- `ors_delete_rec(rec, queue)`: A record is deleted from the queue.
- `ors_new_event(e,r)`: This routine binds an event variable to an execution record.
- `ors_test(e,s) result(finished)`: This routine implements a *test* inquiry, where `s` is the SDA-handle of the caller. A blocking MI is sent to the owner of the event e (which is the SDA that has issued the MI to which the event is bound). The result of this MI is a logical flag indicating the execution progress of the MI bound to the queried event.
- `ors_wait(e,s)`: This routine is similar to `ors_test` except that it implements a *wait* inquiry. Thus, it will only return if the MI bound to the queried event has finished its execution. The counterpart of both routines, ors_test and ors_wait, on the callee side is the routine
- `ors_handle_inquiry(r,c,a)`: This routines handles an inquiry `a` (which may be a *test* or a *wait*) on a specific asynchronous MI referred to by `r`. `c` is the execution record of the inquiry. In case of a *test* the *finished* component of `r` is immediately returned to the caller. In case of a *wait* the caller is blocked until the the queried MI eventually has returned.
- `ors_handle_return(r)`: This procedure is invoked when an SDA receives an execution acknowledgment for an issued MI. It checks whether all the results have been received, cleans up the outqueue and informs all SDAs waiting on the return of the MI (i.e. all SDAs which have issued a *wait* on the event bound to the MI) that it is finished. In case of a synchronous call the whole record can be deleted from the outqueue, while we have

to maintain some minimal information about the MI (including the *finished* flag and the *ID*) in case of an asynchronous call because inquiries may still occur.

4.2.1 Interaction between Distributed SDAs

To allow for data parallel execution, an SDA may be distributed across multiple nodes. Thus, depending on the underlying system, an SDA consists of multiple threads or processes. In order to properly synchronize them we need to combine them in a so-called SDA group (in a multithreaded context this is similar to the notion of ropes [20]) and introduce a master/worker relationship among them.

Interactions between distributed SDAs might require data redistribution and Figure 6 shows the method invocation process for this case. Some more remarks on distributed SDAs can be found in Section 4.4.

4.3 The Opus Compiler

The final component of the Opus system is the Opus compiler (OC). The compiler restructures the Opus code and produces blocks of code that utilize the functionalities provided by ORS. More specifically, the compiler splits the code of an SDA into a set of subroutines which implement the SDA semantics. The structure of these subroutines is independent of the actual application and is fixed in so-called *compilation templates*. These templates are filled in by the compiler using the specific application code.

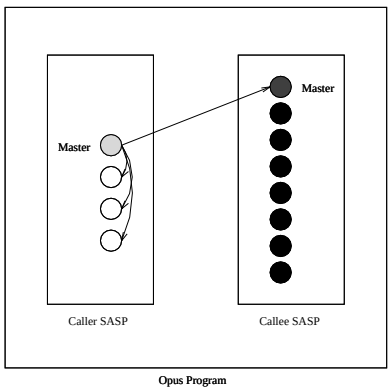
The Opus compiler is realized as an integrated part of the *Vienna Fortran Compiler (VFC)* [3]. As already shown in Figure 2 the input program is transformed into an HPF-conforming program with calls to ORS. This HPF program is subsequently compiled by VFC, producing a Fortran 90 program with calls to both the ORS and the VFC runtime systems. By integrating the OC with VFC we can specifically focus on the tasking issues of Opus and allow VFC to handle the data parallel portions. Therefore, OC needs only to restructure SDA code, and leaves the remainder of the code as well as all the internal code of SDA methods which is not concerned with MIs to be handled by the VFC compiler.

The Opus execution model imposes several requirements on how an SDA is compiled:

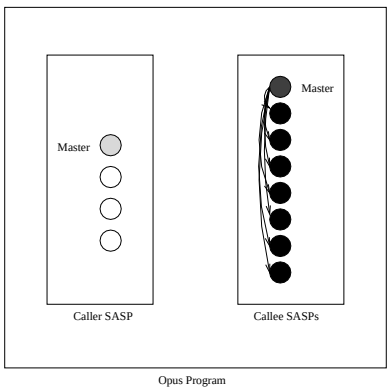
- An SDA executes in a separate address space (SASP).
- Independently of its execution state an SDA should be able to receive MIs.
- Multiple SDAs may execute on one node.

As already discussed in Section 4.1 the mapping of SASPs onto nodes can be *process based* or *thread based*. In the following we assume a *thread based* mapping and give some remarks on a process based implementation in Section 4.4.

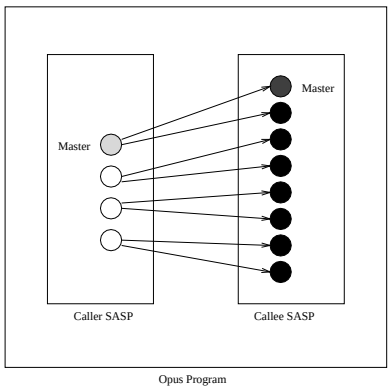
By compiling SDAs into separate threads multiple SASPs can be efficiently mapped on the same physical resources. However, within an SDA there is the need for multiple threads as well because



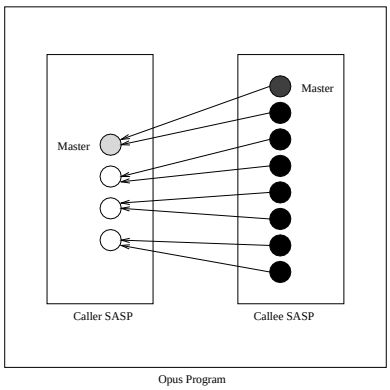
1. Caller master sends an MI to callee master with actual argument distributions and notifies its workers.



2. Callee master notifies its workers. All components of the caller and callee compute communication schedules.



3. Caller components send data messages to appropriate callee components directly.



4. When method execution has finished, the callee components send any return messages to the caller components. This completes the MI.

Figure 6: Illustration of the MI Process for Distributed SDAs

we need a component that is able to receive MIs independently of the SDA's execution state. Hence, one can think of a hierarchical thread structure where a SDA thread is subdivided into two independent threads communicating via a shared memory segment. As shown in Figure 7 the three components of an SDA are:

- A shared memory area, in which the *MI-queues* as discussed in Section 4.2 are allocated.
- The *Server Thread* which receives MIs, constructs execution records and places them into the inqueue.
- The *Execution Thread* which retrieves records from the inqueue, evaluates the "when-conditions" and executes the respective methods.

Synchronization between the threads is handled by their access through the shared queues. In

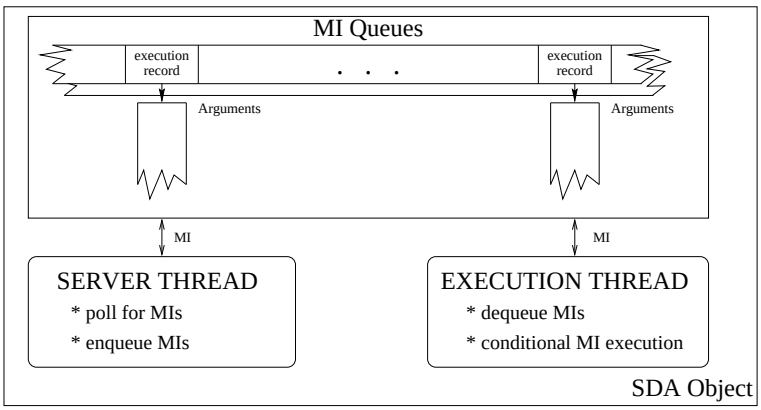


Figure 7: Structure of an SDA Object

the following we discuss both threads in more detail, introducing their compilation templates.

The Server Thread Although the primary task of the server thread is to receive and enqueue MIs while the computation is carried out by the execution thread, it is also capable to respond directly to inquiries about the state of an MI. This allows such queries to be "short-cut" and answered immediately, rather than being enqueued for service by the execution thread. Such queries occur within the context of event management (*wait* and *test*).

Figure 8 shows the compilation template for a server thread. Once the server thread is created it starts an infinite loop in which it is waiting on incoming MIs. This call is blocking and the underlying thread system ensures that the server thread is suspended if no messages are available. After having received an MI the server thread takes the appropriate steps dependent on the *action* that has to be performed in response to the MI. The server thread is able to distinguish between four different actions:

- *Inquiries:* An SDA has issued a *wait* or *test* request on an event which is bound to an MI issued by the receiving SDA. The server thread first has to look up the outqueue in order to retrieve the matching execution record and then calls ORS which will handle the request.
- *Execution Acknowledgment:* If an MI has finished, the callee sends back an execution acknowledgment which is received by the server thread of the caller. Similar to inquiries, first the matching execution record has to be retrieved from the outqueue and then the ORS is invoked in order to handle the return.
- *Method Call:* An SDA has issued an MI asking for the execution of a method. Depending on which method should be executed the server thread receives all the input arguments and adds them to the execution record which in turn is inserted into the inqueue.
- *Termination:* This flag indicates the server thread to finish its execution.

The compiler has to fill in the appropriate calls to ORS for receiving the arguments of MIs. By compiling the exchange of actual arguments we can avoid additional copying that would occur if the ORS has to receive the arguments without knowing their actual layout.

```
SUBROUTINE sda_name_server
  TYPE(ors_execution_rec), POINTER :: b,c
  TYPE(ors_mi_queue), POINTER :: inqueue
  TYPE(ors_mi_queue), POINTER :: outqueue

  DO  ! forever
    CALL ors_receive_mi(b)  ! blocking

    SELECT CASE (b%action)
    CASE (wait_id, test_id)
      c = ors_get_rec(b,outqueue)
      CALL ors_handle_inquiry(c,b,b%action)

    CASE (exec_ackn_id)
      c = ors_get_rec(b,outqueue)
      CALL ors_handle_return(c)

    CASE (method_call_id)
      SELECT CASE (b%method_id)
      CASE(1)
         ! receive arguments for method 1
        ...
      CASE(n)
         ! receive arguments for method n
      END SELECT
      CALL ors_insert_rec(b,inqueue)

    CASE (termination_id)
      EXIT
    END SELECT
  END DO
END SUBROUTINE sda_name_server
```

Figure 8: Compilation Template for the Server Thread

The Execution Thread The execution thread (cf. Figure 9) contains all of the method code, which is unaltered by the Opus compiler except for the method calls, as well as the code required to evaluate the "when-conditions" for conditional SDA method invocation. The execution thread also contains a generic "execution loop" that looks in the inqueue for work. The execution thread is implemented as a F90 subroutine whose body is the execution loop; the method procedures are compiled to internal subroutines as well as the "when-conditions" which are transformed to internal logical functions. The execution loop repeatedly checks the inqueue for MIs. If none are found, the execution thread is suspended. Otherwise, the procedure associated with the MI is executed, given that the associated "when-condition" function evaluates to true. The implementation of the execution thread guarantees that no two method procedures of an SDA can execute in parallel which is in conformance with the monitor-like semantics of SDAs.

In particular, the execution thread performs as follows:

- After a call to ORS in order to initialize the SDA (in particular the outqueue and inqueue)

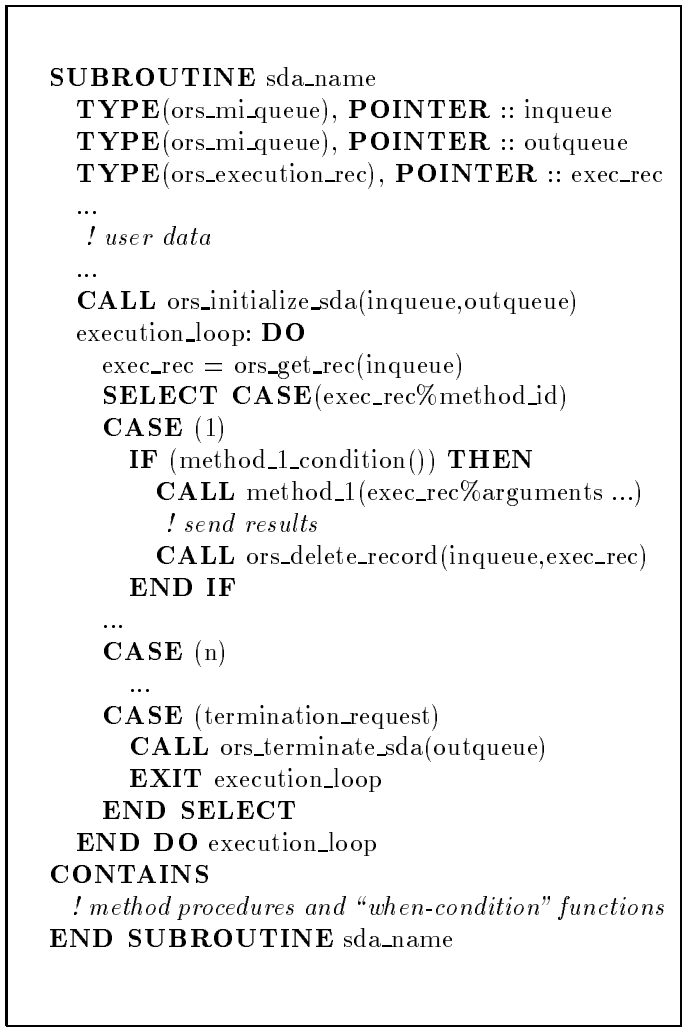


Figure 9: Compilation Template for the Execution Thread

the execution thread enters the *execution loop*.

- In the execution loop the inqueue is checked for MIs. If there is an execution record available it is processed as follows:
  - Depending on the method which should be executed (identified by the `method_id` component of the execution-record), the matching *when* function is evaluated.
  - If the "when-condition" is not satisfied, the loop enters another iteration picking the next available record from the inqueue. Otherwise the method is executed and ORS is subsequently asked to send back the results to the caller. Finally, the record is deleted from the inqueue.

Method Invocation As said before, the code of method procedures remains unaltered by OC except for MIs[1]. Figure 10 shows the compilation template for different kinds of MIs:

[1] The synchronization mechanism based on events is also considered to be an MI.

```
SUBROUTINE method_1(b,...)
  TYPE(ors_sda_type), POINTER :: b
  TYPE(ors_execution_rec), POINTER :: r
  TYPE(ors_event) :: e
  ...
   ! CALL b%m1(...)
  r = ors_new_rec(b,method_id(b%m1), arguments)
  CALL ors_insert_rec(outqueue,r)
  CALL ors_send_synchronous_rsr(r)
  ...
   ! e = SPAWN b%m2(...)
  r = ors_new_rec(b,method_id(b%m2), arguments)
  CALL ors_insert_rec(outqueue,r)
  CALL ors_new_event(e,r)
  CALL ors_send_asynchronous_rsr(r)
  ...
   ! wait(e)
  CALL ors_wait(e,ors_my_sda)
  ...
END SUBROUTINE method_1
```

Figure 10: Compilation Template for Method Invocations

The first step is the creation of a new execution record. Note, that the argument component of the execution record also holds pointers for results and arguments with intent OUT or INOUT, thus the ORS routines for receiving the results can make use of these addresses and do not need to make additional copies. This record is then inserted into the outqueue and, if an event was specified, the event variable is bound to this record. Dependent on the execution type (*synchronous* or *asynchronous*) a specific call to ORS is made asking for sending over the request. This call will return immediately (in the case of an asynchronous call) or it will block until the MI has returned. A call to the intrinsic subroutine *wait* is simply compiled to a respective ORS call. The intrinsic function *test* is compiled analogously.

4.4 Practical Remarks on the Implementation

We gave a detailed design description of the Opus system above. However, the actual implementation needs to modify this "ideal" design to some extent because of interoperability problems between some of the system components as we discuss below.

Thread Compliant Message Passing System Our presented design is assuming a multi-threaded system. This imposes, that the used message passing system has to be thread compliant in a sense as it is specified in the MPI-2 standard [27]. However, current MPI implementations

such as mpich [14] are not thread compliant which causes some changes to the system design.

In particular, we have to ensure that at any time there is only one MPI-call active on a node. We can accomplish that by assigning all the MPI calls to the *server thread* and having a single server thread per node which is able to serve all possible SDAs instead of having a separated server thread per SDA. One of the problems concerned with that is that the server thread can no longer block in the call to `ors_receive_mi` because it has also to send out data at unpredictable times. Hence, the server thread has to actively poll for message which causes an significant overhead.

Process Based Implementation If the underlying system does not allow a mapping of SDAs to threads a processed based mapping has to be applied instead. Hence, also an SDA cannot be internally multithreaded as it is described in our design. In particular, this means that there is only one thread of control which has to fulfill the tasks of both, the server and the execution thread. This can be accomplished by merging the codes of the server and the execution thread. More specifically, the compilation template of the execution thread is used as basis for the new implementation and the code of the server thread template is included into the execution loop. Thus it is ensured that new MIs can be received if no method is being executed. The implementation of the routine `ors_receive_mi` has to be changed such that it is not blocking anymore but does actively poll for MIs.

Another problem within the context of process based implementations is that the underlying message passing system must be able to support dynamic process management. Unfortunately, this is e.g. not possible with current mpich. An implementation based upon LAM [26] could be considered instead.

Data Parallelism We already discussed some of the implications of distributed SDAs in the context of SDA interaction in Section 4.2.1 where we also introduced a master/worker like relationship among the nodes of an distributed SDA. The MI handling described there ensures the same ordering of execution records in all the inqueues of an SDA, thus, there is no need of extra synchronization between the master and its workers when selecting a record for execution. However, the evaluation of the "when-conditions" may involve data replication if distributed data is needed for doing the evaluation. A possible alternative to having all execution threads of an SDA doing the evaluation would be to assign only the master with this task. In this case there is then the need of synchronization between the master and its workers: the master has to signal which record should be executed.

5 Rationale and Related Work

In this Section we put our system design as described above in context to other approaches for systems integrating task and data parallelism. More specifically, we want to highlight alternative design possibilities for the system components and give the reasons why we came up with our specific design.

5.1 System Support

In Section 4.1, we identified the functionalities the underlying system has to provide. The key requirements are *multithreading* and *communication*. Thus, we could have employed one of the packages that combine these features, such as Chant [18], Nexus [12], or Panda [4]. The advantage of using such packages would be that they provide a high level of abstraction for both multithreading and communication, often using an interface similar to the well known pthreads interface. With help of these packages there would be no need to care about the low-level details encountered when integrating multithreading and communication, such as direct communication between threads or proper thread synchronization. Moreover, most of these packages also provide support for a remote service request abstraction.

However, for an Opus implementation as we have described in this paper, we felt that the disadvantages of using a high-level runtime system like Chant or Nexus outweighed the advantages of the features they offer. There are several reasons for this. First, many of the features provided by these packages, such as remote service requests, do not implement the proper semantics of SDAs, such as conditional execution of methods and distributed method arguments. Second, because we have chosen to compile the SDA specifications as much as possible, the requirement for sophisticated runtime support is greatly reduced. Instead, only a small set of lightweight interfaces for threads and communication is desired. Third, there is a serious software engineering problem with integrating a large runtime package with an existing HPF runtime system such as VFC. This is due in large part to the inability of most runtime system packages to change their behavior in accordance with the needs of different users [17]. Finally, if all one needs is basic threads and communication, then using these higher-level runtime systems often just adds unwanted overhead to the performance of the operations. For example, although it is possible to access MPI calls from within Nexus [11], doing so is much slower than accessing the machine-specific MPI implementation directly.

In light of these disadvantages for using high-level runtime support systems, we decided to use low-level communication (e.g. MPI, TCP/IP) and multithreading (e.g. pthreads) packages directly as basis for our ORS implementation. By using these standardized packages we can easily integrate the ORS with the VFC runtime system, thus enabling us to port to another platform that supports VFC with little effort.

5.2 The Opus Runtime System and the Opus Compiler

The main component of the Opus system is the Opus Compiler which targets on the Opus Runtime System. The discussions of the compiler and the ORS are tightly related hence we combine these discussions in this Section.

One of the major design decisions was where to put the borderline between the compiler and the runtime system. In previous work on the implementation of Opus [19], we assumed that the runtime system would provide a generic interface and manage most of the coordination between SDAs. The task of the compiler was only to insert calls to the runtime system where appropriate. This approach, which is commonly used to provide an initial implementation of a new language, assumed a fairly sophisticated runtime system based upon Chant [18]. However, this approach had some major drawbacks. In order to provide a generic interface to the compiler the runtime system was supposed to be implemented in C/C++, since Fortran 90 does not

support any abstraction for generic data types. This meant that all the data needed for method invocations had to be converted from Fortran 90 to C/C++, stored and managed there, and subsequently be converted back to Fortran 90. This conversion, however, is a non-trivial task since there are major differences in the storing schemes and argument handling between C/C++ and F90. Moreover, storage schemes and argument handling are not standardized in F90, thus, any attempt to interface F90 with C/C++ would be compiler dependent and not portable anymore. Another problem with that approach would be generating and using C-wrappers for all the HPF routines, resulting in additional calling overhead.

The same problems arise when using other high level coordination libraries like e.g. KeLP [9] which is also a C++ library that needs additional conversion of the HPF data and HPF mapping descriptors into its own convention.

Again, for the approaches discussed above interoperability problems with the VFC runtime system would occur, as described in the previous subsection.

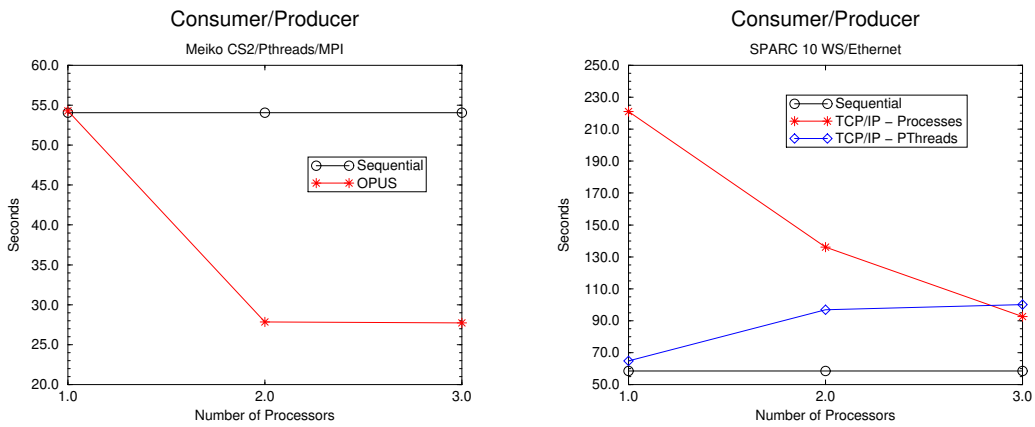
The HPF binding of MPI (HPF/MPI [13]) could probably more easily be integrated with VFC. However, it has some problems in expressing the whole flexibility that Opus needs and it is a system which is primarily considered to be used by a programmer rather than by a compiler.

Our decision to let the compiler do most of the work and using only a small ORS written entirely in F90 was mainly driven by the disadvantages in using other languages than F90 as described above. Although the task of the compiler is limited at the moment, in fact, it only fills in compilation templates, making extensive use of the compiler may have further benefits in the future. By using the compiler we have the possibility to apply optimizations wherever possible that prevent e.g. expensive runtime checks whereas a generalized runtime system cannot skip them. In addition, the compiler could recognize and exploit further parallelism potentials like intra-SDA parallelism what is a major topic for future research.

Related coordination approaches that make use of a compiler are e.g. Fx [16], Fortran-M [10], or Orca [2]. Fx does not need any runtime support since it has a quite simple tasking model similar to the tasking facilities in HPF-2 (in fact, HPF-2 took over many ideas introduced in Fx). Fortran-M is based upon Nexus which fits perfectly into the Fortran-M model, however, Fortran-M is a purely task parallel language thus the problems of Nexus in a data parallel context do not arise. Similarly, Orca was initially designed as a task parallel language based upon Panda. Subsequently, Orca was extended towards data parallelism [21] using similar concepts as Opus. However, in contrary to Opus, Orca is not an extension to an existing data parallel language but a new language where both data and task parallel features have been designed in a way that they integrate well. Hence, Panda was designed to support both task and data parallelism whereas ORS has to be integrated with an existing data parallel runtime system.

6 Implementation Status and Preliminary Results

We implemented a prototype of ORS on the MEIKO CS2 as well as on a cluster of Solaris Workstations. The implementation was mainly done in Fortran 90. The ORS is based on mpich [14] (on the Meiko) and on TCP/IP [23] (on Workstations), respectively, as well as on the native Solaris pthreads implementation. This prototype is currently restricted to the task parallel features of Opus.



(a) (b)

Figure 11: Preliminary Results for the Consumer Producer Problem

We have hand-compiled a simple version of the producer/consumer problem (cf. Figure 1) where one producer and one consumer act on a bounded buffer. The preliminary runtime results of this hand-compiled program can be found in Figure 11(a) for the Meiko and in Figure 11(b) for the Workstation-Cluster.

From the results for the Meiko it can be seen that our implementation introduces only a small overhead to the sequential version using one processor. We can achieve almost perfect speedup onto two processors, whereas using more processors does no lead to any additional performance gain. This is due to the internal parallelism of the problem which is restricted because we simulate only one producer and one consumer.

The situation on a Workstation-Cluster differs significantly from the Meiko since we cannot make use of the fast interconnection network but are using an Ethernet connection for communication. Therefore, executing the program on more than one processor slows down the execution time significantly because of the communication overhead. Moreover, we have tested the program using a process based implementation instead of the thread based one. As it can be easily seen a process based approach introduces a significant overhead if more than one SDA are mapped onto the same processor. This is due to the inability of explicitly scheduling of processes. The situation becomes better if we enlarge the number of processors used, so that eventually only one SDA (and consequently only one process) is mapped onto a processor. However, the runtime on three processors is still worse than the sequential one because of the communication overhead.

In Figure 12 the results for an extended producer/consumer example on the Meiko can be found. Here we have executed larger tasks on different numbers of processors where the whole produce and consume task is distributed over differing numbers of SDAs reaching from one to 16 producers and 16 consumers, respectively. Again, it can be seen that the Opus implementation causes only limited overhead to the sequential version and that the problem scales well up to 32 processors. Moreover, having multiple SDAs executing on the same processor (as it is the case if the number of producers and consumers is larger than the available processors) does not add an significant overhead and can indeed be advantageous because of a better overlapping of communication and computation.

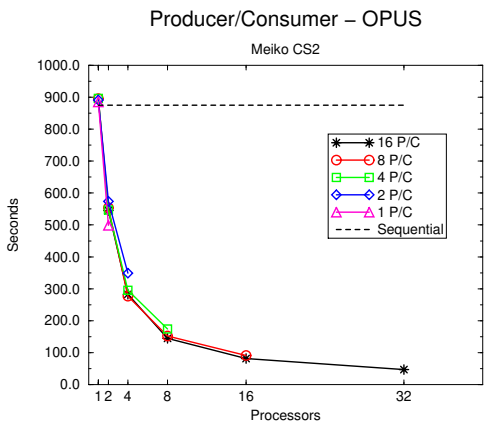


Figure 12: Extended Consumer Producer Problem

7 Conclusion and Future Work

In this paper we presented our major design decisions for the Opus system and showed how it can be efficiently implemented. Some requirements were identified every platform has to provide for Opus. In order to enhance the flexibility and portability of the Opus system, only low level standardized packages for both communication and multithreading have to be available on any target architecture.

We described in detail the runtime behavior of an Opus application and provided a specification for the supporting runtime system as well as for the restructuring compiler.

Our approach makes intensive use of a restructuring compiler which generates an HPF-conforming code expressing the Opus semantics. Thus our approach is in contrary to runtime based approaches like e.g. KeLP [9] or HPF/MPI [13] where a runtime library is used to coordinate different tasks. By using a restructuring compiler our implementation is open for future extensions or modifications of the Opus language that might need more advanced compiler techniques (like e.g. the exploitation of intra-SDA parallelism). Another benefit of the compiler approach is that we do not need to tackle the interoperability problems of Fortran 90 and C or C++ since all of our resulting code and most of our runtime system is written in Fortran 90.

Future work will focus on the implementation of the Opus compiler which will be realized in close relationship with the HPF compiler VFC [3]. Moreover the Opus runtime system has to be integrated with the VFC runtime system. For implementing the Opus compiler we make use of modern compiler construction tools like the *Cocktail* tool box from GMD [15].

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