ABSTRACT

Most simulation problems are inherently concurrent, and traditional approaches in trying to simulate concurrent problems by serializing them result in inefficient and complicated solutions. This paper presents the design and implementation of an Airport Simulator based on the entity-life model, the use of which results in a clear and intuitive design. It is essential to choose a programming language with concurrent features for concurrent simulation. The Airport Simulator is implemented in Ada for its strong and effective tasking features.

1. INTRODUCTION

The development of modern parallel languages, such as Ada, Modula, Concurrent C, etc. in recent years coupled with the advent of low cost microprocessors has made concurrent solutions to simulation problems more viable than ever. Such a concurrent solution in the Ada programming language could lead to significant improvements in the design, testing, run-time speed, code reusability, and life-cycle maintenance of the simulators.

The entity-life model [Sanden 1989] provides an efficient design principle that can be used to reduce a concurrent problem to a set of sequential problems. The entity-life model suggests that each independent thread of events in the real world be modeled as a task - the Ada language construct to represent an independent, asynchronous thread of events. In this article, the design and implementation of an airport simulator, based on the entity-life model is presented.

Most real world simulation problems can be naturally expressed as a set of physical entities, each having its own thread of events and interacting with the other entities in the problem environment when a need arises. In traditional approaches to simulation much effort is wasted in serializing a problem environment which is inherently concurrent. Thus, when the entities in the problem environment have a strong time dimension, that is they often change state during the course of their existence, it is more logical to express them as software processes than as data. Prior to the development of languages such as Ada, incorporating software processes into a program meant that the programmer would have to write a language extension to support concurrency or even if the language did support a rudimentary form of concurrency he would have to use explicit commands to control their activation, interaction, etc. The problems with such approaches precluded the use of concurrent simulation techniques to most situations.

The Ada language on the other hand has concurrency intrinsic to the language and provides a logical, procedure-like interface between tasks, known as the rendezvous. Thus an Ada oriented design approach can simultaneously take advantage of tasking features as well as other modern language features available in Ada. These advances in language features combined with the new techniques available for design of concurrent software present a strong case for using concurrency in simulation, and also for using Ada as the simulation language.

While a few process oriented discrete event simulation languages, or packages [Thesen et al. 1983], are available to the programmer problems of documentation, time spent in learning a new language etc. are inhibitive. Moreover, the internal design for the simulation languages is not well documented in most cases. Such a situation combined with the fact that 90% of most simulation languages consist of general purpose code and 10% of application specific code written in the special purpose simulation language or a vendor supplied subroutine package [Thesen 1987], presents a case for writing simulators using general purpose languages as opposed to special purpose simulation languages. Portability considerations may also be taken into account while making a decision about the language to use. The Ada language [Gehani 1988], contains many unique language constructs and software engineering techniques such as data and process abstraction, object oriented design, information hiding, and has therefore been chosen for this simulation project.

2. SIMULATION MODELS

2.1 Classification

Simulation languages have been classified by the modeling viewpoint that can best be expressed using that language. These fall into the categories of Event, Transaction and Process-oriented. These are modeling viewpoints as opposed to language viewpoints of object-oriented modeling and data abstraction detailed in [Gomaa 1989]. In an event oriented view, the focus is on events, which alter the state of the system. The modeler can visualize the system as entities flowing through event sequences. Each type of event is represented in the simulation model by a software routine. In a transaction oriented view, the focus is on entity with attributes (transaction) flowing through the system. The simulation model describes all possible paths through the system, dealing with each entity independent of others. This view is natural to the modeler. The process oriented view focuses on the process, which is an event sequence. As such, the process includes events and the time delays between them. Each unique process is modelled by a process routine. Processes must become active and passive to model the flow and interactions of entities through the system. This view allows a natural correspondence with the abstract model for both the modeler and the programmer.

2.2 The Entity-Life Model

Various design strategies have been suggested for modeling a system as a set of concurrent processes, and most of these originate in the domain of real time systems. The entity-life modeling approach suggested by [Sanden 1989], seems to be more applicable to problems outside the domain of real-time systems. Moreover, the other modeling theories tend to address function decomposition first, and then deal with task decomposition. The entity-life model on the other hand has task decomposition as its first objective, resulting in a clear and intuitive design which is isomorphic with respect to entities in the real world system that is being modelled.

Advantages of the entity-life model:

1. It results in a design which is isomorphic with the entities in the real world.

2. Each concurrent process becomes an information hiding unit, thereby encapsulating not only data structures representing the real world entities but also their current
This is sometimes very important in a simulation because if the object exists in the simulation it may be represented by a task type, with one instantiation of the task for each of the entities. Melde and Gage (1989) suggest the following three phases for the entity-life model:

1. Identifying the entities in the real world model and mapping these onto tasks and other data structures.
2. The packaging phase deals with defining the modules and their interface between them. Also, further decomposition into packages takes place at this stage.
3. The implementation phase deals with the detailed elaboration of the modules defined in the previous stages.

According to the entity-life model, all physical entities, those that exist in the real world can be manipulated by a task. Each airplane can be manipulated as an active element of the language called an entity. This makes it very important that the simulation be able to manipulate itself as objects in the system. It may be represented by a task type, with one instantiation of the task for each of the entities.

The single most important feature of the Ada language is the tasking facility which allows the programmer to express concurrency and nondeterminism. These are the most important issues in modeling real world situations, and these have not been addressed previously. Hence, our approach in this simulation effort is to model the simulation in an entity-life model and to signify that the most important and rapidly changing objects in our simulation are active processes as opposed to passive data.

Such a model has the advantages of simplicity of design, increased run-time speed, portability and ease of development and testing effort over traditional methods of simulation which require serialization of concurrent activities, complicating the design and making the simulation slower.

According to the entity-life model, all physical entities, those that are existing in the real world and can manipulate their own state should be implemented as active elements of the language, i.e., tasks.

These tasks should manipulate themselves completely and should interact with other tasks only when absolutely necessary. This decreases global information in the system to a large extent. Each task should be able to do primitive tasks of input and output, on its own. This should be recognized, since if there are many concurrent tasks writing to the same screen at the same time the screen may become messy.

3. THE ADA LANGUAGE

3.1 Language Features

The following is a brief description of some of the important and unique language features of Ada used in the simulation.

(a) Tasks: Parallel processes in Ada are called tasks. A task executes independently and asynchronously, communicating with other tasks through message passing, using the ACCEPT and ENTRY statements. A task may call another task at its ENTRY, and they can participate in bidirectional communication (termed rendezvous) after the called task accepts the entry call. A task is defined into two parts, task specification, and task body. The task specification presents the external interface to the task, and the body describes the actions performed by the task.

Features of the tasking Model

1. Provides a simple mechanism for communication without the need for explicit synchronization statements.
2. Provides for simultaneous bidirectional communication.

3. Instructions are executed by the called task on behalf of both the participating tasks.
4. The calling task must know the name of the called task.
5. A calling task can call only one other task and can only be in one entry queue of tasks waiting for a call to be accepted. A called task on the other hand can wait for any of many different types of calls and can have many queues of calls (one for each entry) waiting for its attention. The tasking model allows for the called task to have greater control over the rendezvous.

(b) Packages: Packages are information hiding units. They are defined in two parts, package specification and package body. Logically related entities and the operations that can be performed on them may be grouped into a package specification and the implementation details in the package body, thus presenting a high-level interface to users of the package while hiding the implementation details.

(c) Conditional rendezvous: The three kinds of select statements, Selective wait, conditional entry call, and timed entry call, facilitate conditional rendezvous between tasks in various situations.

(d) Access Types: Access types permit dynamic creation of objects of a predefined type, at runtime. When this declaration is used with a task type, it facilitates creation of any number of tasks of the predefined type at runtime.

(e) Termination: Ada provides for the terminate statement to ensure orderly and cooperative termination of tasks.

The working of the three kinds of select statements, the access type declaration and the terminate statement, are described in more detail in section 4.2.1, where they are used in the implementation of the airport simulator.

3.2 Ada and Other Languages

The most important strengths of Ada lie in concurrency but calling Ada a language suited only to real-time applications is far from the truth. It is a true general purpose language with all the traditional language features. It is portable like C, supports object oriented programming principles like C++, and has concurrent facilities like MODULA.

It is different from other languages because features to support concurrency are intrinsic to the language, i.e., it does not have any explicit task activation, suspend, resume or synchronization primitives such as message passing.

In addition to the language features mentioned in section 1, features such as strong typing, rigorous syntax checking, separate compilation, etc., save development costs. This will be the biggest criterion in future projects, as a result of the reverse trends of increasing software costs and decreasing hardware costs.

The Ada run time environment is responsible for run-time scheduling of the tasks therefore, it can take advantage of as many processors as are available to the simulator, thus enabling porting of the simulator from a development system to an operating system which might have a different no. of processors.

4. THE AIRPORT SIMULATOR

4.1 Problem Description

The following is a short description of the airport which we wish to simulate.

(a) Airplane: There are two classes of airplane that visit the airport distinguished by their weight, light and heavy. Each airplane can be identified by a unique flight number and has a particular amount of fuel that keeps decreasing with respect to time while waiting to land, the rate of decrease being determined by its weight class.
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(b) Airport: The airport has two runways, Heavy Runway which can service planes of any weight class and Light Runway which can service light planes only. Each of the runways can be used for either takeoff or landing, but in case of emergency the landing airplane is given a higher priority. There are two runway controllers in the airport, one for controlling each of the runways. The job of the runway controller is to take the flight number of the requesting airplane from a queue and engage the airplane in a two-way conversation in order to provide the airplane with relevant weather, runway information, etc. and to guide its landing or takeoff.

Each of the runway controllers has associated with it a queue of planes waiting to use the particular runway. The Air Traffic Controller (ATC) queues the requests into one of these two queues and the runway controllers dequeue each waiting plane and guide its use of the runway.

(c) Operation: Any airplane wishing to use one of the runways issues a land_request or takeoff_request to the ATC. The ATC then checks the queues associated with each of the runways and decides if the request can be serviced without a conflict with any of the planes that have already been accepted. If it can be accepted, it is put in one of the queues, else the airplane is informed that it has been rejected.

The entity structure for the plane can be represented by an entity diagram as shown in figure 1.

4.2 Analysis, Design and Implementation.

The entity-life model vastly simplifies the design of the simulator, and makes the design easy to understand.

4.2.1 The Modeling Phase

The modeling phase begins with the identification of the major real world entities and mapping them into tasks and other data structures. A context diagram is a high level functional representation of the various entities involved in the system. Figure 2 shows the context diagram of the Airport simulator. The modeling phase identifies concurrency within the airport simulator.

Step 1: The following entities can be identified in the airplane simulator model.

1. Airplanes
2. Airport consisting of
   (a) Air Traffic Controller (ATC),
   (b) Runways (2) Heavy Runway and Light Runway,
   (c) Runway controllers (2), Light Runway Controller (LRC) and Heavy Runway Controller (HRC).
3. Terminal to receive instructions from and display results to.

These entities and their interactions can be represented by a further refined context diagram. Notice that all entities that have a time dimension should be modelled as tasks and are represented by shaded circles in figure 3.

Step 2: The next step is to further refine the design by identifying concurrency within each module. This process is done repeatedly until we cannot find further concurrency within each module.

These steps result in further splitting the airport task into the three tasks, 1. Air Traffic Controller. 2. Light Runway Controller. 3. Heavy Runway Controller.

Step 3: At this stage we have to make decisions on abstract entities which have a time dimension. This step results in one more task, the Random Request Generator to randomly generate flights for the simulator to process. Statistics task collects statistics on all planes and analyses them. Dynamic Queues may also be represented by tasks since they have a definite time dimension.

1. Random Request Generator -- Randomly generates flights.
2. Statistics

![Figure 1. Entity Structure for Plane](image-url)
Figure 2. Context diagram for an Airport simulator

Figure 3. Context diagram for Airport Simulator.
Shaded Objects represent real-world entities.
Unshaded objects represent abstract entities.
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- Collects statistics on all planes.
- Queue for the heavy controller.
- Queue for the light controller.
- Buffer task to record status of H-queue
- Buffer task to record status of L-queue

Step 4: The next step is to identify tasks to handle specific I/O devices. This results in two tasks

1. User Input task.
2. Display Task.

At this stage, some of the tasks may be combined to simplify the design. We combine the display task with the statistics task, to yield a simpler design.

4.2.2 The Packaging Phase

The packaging phase consists of defining the way tasks, packages, subroutines and functions are grouped together so that the resulting model is logical and follows the objectives of information hiding and data abstraction. This phase follows three steps.

1. Determine interfaces for communicating units, such as tasks and packages.
   a. Define entry points for each task.
   b. Determine parameters and in/out modes for each rendezvous.
   c. Specify exceptions raised and handled.
2. Package global data types and constants.
3. Package hardware dependent features for each device.

This phase results in four packages for the Airport simulator, Air Facilities, Ground Facilities, Random Requestor and Support Package.

Package Air Facilities
- specification and implementation of the entity Airplane.

Package Ground Facilities
- specification and implementation of the remaining entities, of the simulator.

Package Random Requestor
- the task Generator which on request from the user randomly generates flights to be processed by the simulator.

Package Support Facilities
- packages that help in building Air Facilities and Ground Facilities, such as screen management features, Math functions, Random no. generation functions etc.

Specification of package GROUND_FACILITIES, package AIR_FACILITIES is

end ATC;
task H-QUEUE is
entry START_H-QUEUE(P,D1,D2,D3:in INTEGER);
entry ADD_TO_Q(A:in PLANE_REC ADDR:in T-ID);
entry NEXT_JOB(ADDR:out T-ID);H1:out FLY_TIME;L2:out FLY_TIME);
end H-QUEUE;
task H-STAT is
entry CLEARED(H1:in FLY_TIME;H2:in FLY_TIME);
entry READ_STATUS(w1:out FLY_time;w2:out FLY_time;
end H-STAT;
task H-RC is
entry START_H-RC(P:in INTEGER);
entry wakeup;
entry FINISHED;
end H-RC;
task L-QUEUE is
entry START_L-QUEUE(P,D1,D2,D3:in INTEGER);
entry ADD_TO_Q(A:in PLANE_REC ADDR:in T-ID);
entry NEXT_JOB(ADDR:out T-ID);L1:out FLY_TIME;L2:out FLY_TIME;R-STATUS:out STATUS);
end L-QUEUE;
task L-STAT is
entry CLEARED(L1:in FLY_TIME);L2:in FLY_TIME);
entry READ_STATUS(w1:out FLY_TIME;w2:out FLY_TIME);
end L-STAT;
task L-RC is
entry START_L-RC(P:in INTEGER);
entry wakeup;
entry FINISHED;
end L-RC;
task DISPLAY is
entry START_DISP(d:IN int-array);
entry CLEARED-BY-CONTROLLER(A:in PLANE_REC ADDR:in INTEGER);
entry CLEARED-BY-ATC(A:in PLANE_REC N:out INTEGER);
end DISPLAY;
task USER-INPUT is
entry START_INPUT(P:in integer);
end USER-INPUT;
end GROUND_FACILITIES;

Specification of package AIR_FACILITIES:

with PLN_TYPS; use PLN_TYPS;
with FIFO; use FIFO;
with QUEUES; use QUEUES
with SMG; use SMG;

Together these packages define the objects airplane and Priority Queues, and with operations that can be performed on them such as adding a plane to a queue, deleting from a queue. The SMG package defines screen management functions.

package AIR_FACILITIES is
  type AIRPLANE;
  type T-ID is access AIRPLANE;
  type AIRPLANE is
    entry REQUEST_GRANTED(S:out INTEGER);
    entry REQ_REJECTED;
end AIRPLANE;
end AIR_FACILITIES;

4.2.3 The Implementation Phase

This phase involves expansion of task, package, subroutine and function bodies. The following three pages contain a concise description of the package body GROUND_FACILITIES.
task ATC: This task is responsible for initial communication with airplanes, and to decide whether they are accepted or rejected and if accepted, the request is put in the appropriate queue. It is called through the entry point Land_Request and Takeoff_Request.

Loop: Select
- Check status of Queues and put the flight in one of the queues if the request can be serviced, else notify flight. If it is a heavy plane, only H-Queue needs to be checked.

or
- Add flight to appropriate queue if possible.

or
- Terminate;
End select;
End loop;
End ATC;

task H-Queue: This is the dynamic queue for the Heavy Runway Controller (HRC). It acts as a buffer between the HRC and ATC. ATC adds to the queue and HRC removes flights for processing. It is accessed by ATC through the entry point Add_TO_Q, and by the HRC through the entry point Next_job. Implementing this dynamic queue as a task serves three purposes:

1. Ensures that the queue is accessible at all times.
2. Ensures mutual exclusion among the tasks accessing the data.
3. The guards used in the select statements also ensure priority access and is to be kept busy all times.

Loop: Select
- Update number of planes accepted, land, and takeoff.

or
- Get next job from H-Queue.

end select;
End loop;
End H-Queue;

tasks HRC and LRC: These are the two runway controllers, that control the two runways. These two tasks control the runways which are the most important resources of the airport and hence should never be kept idle. The controller calls the airplane to signal it to start landing, and also guides it during the takeoff-landing process.

Loop: Select
- Get next job from H-Queue.

end select;
End loop;
End HRC;

tasks H_STAT and L_STAT: These tasks are introduced to remove the dependency among tasks that would otherwise result in starvation or perhaps deadlock.

The ATC has to get information from the controller on the status of the queues and runways, and the time it will take for the controller to service the present takeoff - landing that it is handling. In order to obtain this information the ATC would have to call the Queues and the controllers to find out about their positions, each time it receives a request from a plane. This could lead to a situation in which the ATC is always waiting for one of the controllers and hence cannot accept requests until it has received a response from both controllers and both queues. The H_STAT task is always available to the ATC, while the HRC is servicing the plane and therefore does not delay the ATC.

Loop: Select
- Get information on status of H-Queue and the time at which the last plane to be serviced by controller started to use the runway.

end select;
End loop;
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when CLEARED_COUNT = 0 =>
- When Controller is not waiting for rendezvous with
  this task.
accept READ_STATUS(W1:out FLY_TIME;W2:out
FLY_TIME;T:out FLY_TIME) do
- Calculate wait time for the queue based on information
  provided by controller and time elapsed since then
- and return it to ATC.
end READ_STATUS;
or
terminate;
end loop;
end H_STAT;
task USER_INPUT: This task is a low priority task and facilitates
user input. Since it is a simulation, the user should be able to give his
instructions to the system at all times, without stopping the system,
e.g. he should be able to create more requests, if he wishes to, while
the simulation is running.
loop
- Always looks for input from the keyboard.
- Gives the option to run simulations by time, or by no.
- of simulations,
- and calls the generator to generate planes.
end loop;

Package RANDOM_REQUESTOR
This package contains one task - Generator, which accepts input
from User_INPUT task.
task GENERATOR: This is a background task whose sole
purpose is to randomly generate requests for the simulator, on
demand by the user. It is important that this may not communicate
with the other tasks in any way than by producing requests, in order
that the nondeterminism and randomness of the simulation are
preserved.
loop
- Select
  Accept GENERATE(NO_OF_SIMS:in
  INTEGER;inp_type:in INTEGER) do
    - Each time it is called it loops for a random number
      - of times to generate flight requests, and makes one
        - task for each flight generated and initializes with
          - random values of fuel, flight, no etc.
  end GENERATE;
or
  accept DONE do
    - No more planes to generate.
  exit;
end DONE;
end SELECT;
end loop;
end GENERATOR;

package body AIR_FACILITIES is
  task body AIRPLANE is
    accept INITIALIZE(A_in PLANE_REC; ADDR:in T_ID) do
      - Initializes the plane with values of fuel, request type
        - weight class etc. generated by the Random no.
        - generator.
    end INITIALIZE;
    - Creates a virtual screen for itself.
    - Request ATC for landing or takeoff.
    - Inform display task of its status.
    Select
      accept REQUEST_GRANTED(S:out INTEGER) DO
          - If called by controller to use runway, inform
            - display task
          end REQUEST_GRANTED;
          - delay for time required for plane to land.
          - Delete virtual screen
          - DO DEALLOCATION
          - Reclaim the storage allocated for
            - the task.
      end select;
      or
        accept REQ_REJECTED do
          - DO DEALLOCATION;
        end REQ_REJECTED;
        - Wipe virtual screen
        - DO DEALLOCATION
end select;
begin
Null;
end AIRPLANE;
end AIR_FACILITIES;
The hierarchy of packages results in an order of compilation as
shown in figure 4. The package PLN_TYPs implements the airplane
entity.
The Package FIFO uses the airplane entity described in
PLN_TYPs to implement a First-in First-out queue. Package
QUEUES uses package FIFO to provide a priority queue, and so
on. An arrow from the body of FIFO to the package QUEUES
signifies that the body of FIFO should be compiled before the
package QUEUES can be compiled.
Figure 5 gives a detailed description of the packages used and
their relationship. A rectangle represents a package, and encloses the
functions exported by the package.

5. PROBLEMS ENCOUNTERED

A major problem with the entity model is that each of the
concurrent processes requires much virtual memory. When the
number of real world entities is inhibitive, some real world entities
which do not change state frequently have to be modelled as data
instead of tasks. Moreover, as the number of active tasks increases
the speed of the system decreases.

With the introduction of concurrency the programmer has to
deal with issues peculiar to concurrency, such as circular wait.
Circular wait is a situation in which two or more tasks are waiting
for resources held by each other, and none of them will proceed
further until the resources are available to it. A simple analogy would
be one in which three persons, A, B and C are trying to call each
other. A is trying to call B, B is trying to call C and C is trying to call
A. In the process none of them is able to communicate with the other.

6. CONCLUSIONS

The concurrency features of Ada, combined with the design
principles of the entity-life model proved to be very appropriate to the
Airport simulation problem, which is inherently concurrent. The
tasks resulting from the design based on the entity-life model were
mostly isomorphic to the real world entities they represent and thus
helped make the design simpler in addition to capturing real world
concurrency which is so vital to many applications. The modern
language features of Ada, particularly its concurrency mechanisms,
and design principles such as entity-life modeling clearly demonstrate
the viability of Ada as a language for simulation.

REFERENCES

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164.
Figure 4. Airport Simulator System Dependency Graph

Figure 5. Packages