ALBATROSS
An Operating-System under hard Realtime-Constraints

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Based on the experiences from an autonomous mobile robot project called MOBOT-III, we found hard realtime-constraints for the operating-system-design. ALBATROSS is "A flexible multi-tasking and realtime network-operating-system-kernel". The focus in this article is on a communication-scheme fulfilling the previous demanded assurances. The central chapters discuss the shared buffer management and the way to design the communication architecture. Some further aspects beside the strict realtime-requirements like the possibilities to control and watch a running system, are mentioned.

ALBATROSS is actually implemented on a multiprocessor VMEbus-system.

1. Motivation & Introduction

Why are realtime-aspects so important for our group? Before trying to find an answer to this question, we would like to give a really short overview of the goals in our autonomous mobile robot project called "MOBOT-III" in the form of a definition. An autonomous mobile robot (AMR) is a system which perceives information about its environment in order to use this information for solving a given task. It has to be equipped with an onboard computer-system to do all computations independently and without external intervention. It must be able to explore unknown environments while building maps (of various kinds). Based on these maps the AMR navigates to specified goals while avoiding collisions with fixed or moving obstacles and performs local tasks like identifying and manipulating objects.

From the pool of realtime-problems in this area we will highlight three.

a. Guarantee for actual data

Most of the decisions have to be based on actual data. For example you might think of reflective navigation around a moving obstacle. If the sensor-information (i.e. the deduced map) for the pilot-component is older than about 100 ms (at a speed of 1 m/s), it is impossible to generate a smooth and really reflective track for the vehicle. And of course it is a great security-risk when the robot drives in a "world before our time".

b. Graceful degradation

In a lot of situations the breakdown of one component makes life too risky for the robot and the only answer will be an immediate stop of all motors. But on the other hand, it is not the best idea to stop the robot because a part of, e.g., the object-recognition-component is beginning to hallucinate. In this kind of degradation, the other parts must be able to decide that the output of this component does not make sense any longer and (very important) the crashed part must be isolated, so that this component is not able to disturb the whole system.

c. Keeping on-line in a running system

Testing the robot in a real environment leads directly (usually at the first corner) to the question: "What are the actual internal maps, this (or the next) decision is based on?". One attempt may be to stop the machine from time to time and to look at the internal data. But this is not a realtime-test and of course not the comfortable way. So the optimal solution is to have an insight into the internal data-structures while these are build up in the running system in a way that the robot can not even detect this access.

The above points should be enough to show our motivation to build a realtime-system fulfilling some hard realtime-constraints.

This article will -hopefully- show a couple of significant differences to conventional realtime operating-systems.

In the next chapter we will discuss some main requirements as seen from the task's point of view. The main part follows in chapter 3. There the communication-scheme in ALBATROSS is being highlighted. First as the base of all information-transfers the so called realtime-ports are discussed in detail, then some higher communication-levels are mentioned. The question of the need for a communication-controller follows. Finally the communication-chapter ends with an opposition of transient and cyclic transfers.
Chapter 4 shows some general aspects of ALBATROSS, like the flexibility in different environments or the possibility to keep on-line in a running system. The final conclusion lists the central aspects of ALBATROSS and shows some relations to conventional realtime-systems.

2. Assurances for each task

In this article it is assumed that the underlying hardware is a distributed system with several processors, each of them is used by a single task. Seen from the perspective of a single task communicating with the whole (complex) system, what will be the necessary assurances a realtime-system has to give to this task.

a. Full CPU-power
   All the CPU-time is exclusively reserved for the local task. This sounds easy but there are two main problems deduced by this restriction:
   a-1 No system-interrupts
      The OS has only access to the CPU if the local task is explicitly calling the OS. There can not be any background operation at all (e.g. interrupts for the system time, etc. pp.)!
   a-2 No communication-interrupts
      If any information is arriving via the communication-system, the local task can not be disturbed by interrupts. So the necessary transport-actions must be done by an other processor and the local task will be informed when the task is interested in the new data, not when the new data is arriving.

   Why is this restriction so important in a realtime-system? Every task has to fulfill a couple of operations in an exactly specified maximal time. Unfortunately there is not a practical way to find out the maximal duration of a task under all conditions. But for sure this problem will not become easier when there is an other unknown variable you have to deal with: the really available CPU-time. So the simplest way to determine the real CPU-time for the task is to give all the CPU-time to that task!

   But this is not the whole truth. Some tasks have to use interrupts to access the local hardware - what about them? In such a case the local task is not only responsible for the run-time of the task itself, but also for the interrupt handlers, installed by it. The OS must assure a maximal (and of course short) time-lack between the stop of the task and the beginning of the interrupt-handler. The task has to control (or to know) the interrupt frequency in order to prevent overflows.

b. No direct connection to tasks on other processors
   All the tasks are synchronised implicitly via the flow of data. i.e. a task will start (over) when it gets some newer input data - an explicit trigger is not necessary! The decision to look for and to use new data depends on the internal state of the local task.
   Assuming a task in the system is crashed - so the only effect seen by other tasks is the lack of newer data. They may decide what is to do in this situation (how important the missing information is) but there is no direct connection to this crashed task. In most cases such a connection would be disastrous.

c. Non-blocking access to the communication-system
   Every call for new data or for an export of new outputs must successfully end within a fixed (and of course short) time - even if the communication partner is broken down or in any other possible constellation.

d. Guaranteed actuality of all received information
   This implies guaranteed transfer times but because loss of data is a real thing in a moving system, this restriction may only be approximated by redundant transfers. And so the communication-system has to be able to transfer a new block of data more than once, without blocking any other packet.

Three and a half out of four assurances refer to the communication-system. So it looks like the communication-scheme is playing an important role in the design process of a realtime-system. All of the above constraints are fulfilled in ALBATROSS even if they are not mentioned again in the rest of the article. In the following chapter we will discuss some of the main communication-aspects of ALBATROSS.

3. Communication in ALBATROSS

When trying to satisfy all of the above assurances, there will be two (apparently) contradictory directions of the way to design the communication. Each of the two dispositions leads to standard solutions, when trying to fulfill them isolated. Before discussing the combined solution, we will show the two conventional paths.

a. Couple two processes as loosely as possible
   Regarded from the viewpoint of one processor for one task, this assumption guarantees in a natural manner a kind of graceful degradation. The typical implementations of this philosophy cover the whole bandwidth of message-passing-systems.

b. Assure restrictive transfer times
   The closer two processes are coupled (the fewer communication-layers are between them), the better are the time-assurances for the communication-accesses. So if you like to get a quick transfer, you will fit the two processes close together. Further (if this is still too slow) you will introduce restrictions in the communication-phases (e.g. no interrupts are allowed while reading in a communication-buffer).

It is obvious that solving the two requirements individually will not lead to the optimum. Up to here the article contains only problem-descriptions, so it is time to show some solutions in the following chapters.

3.1. Realtime Ports

Before talking about protocols, we have to define the hardware-environment. The hardware-structure is simple but
effective. There are two independent processors connected via a dual-ported-RAM, i.e., the memory-domains of the processors overlay. What is the definition of a dual-ported-RAM in this context? Both processors may access the same memory-area simultaneously. A conflict at the level of a byte-access has to be solved with some special hardware, in a way that neither side is being blocked and a byte will stay an indivisible element. Access to the dual-ported-RAMarea is only allowed in the supervisor-mode, so only the operating-system may access this critical memory.

The real-time-transfer in ALBATROSS follows a realtime-philosophy which can be described by three short demands:

a. **Consistency**

Information may only be transferred in consistent units, i.e., you have to wait until a complete message is produced. If you do not consider this restriction, you have to define an extra protocol, assuring that there is no way to build a message with packets from different productions.

b. **Actuality**

Newer information has priority over the older one. This is a contradiction to the usual demand of keeping order, because you have to destroy old information at the level of the communication-system, if there is a newer one (of the same class) available.

c. **Availability**

Information must be available at any time. This does not mean that you have to fulfill restrictive time-limits for the producer. There is simply implied that an information is only destroyed when it can be replaced by a newer one.

Following these demands we have designed a really simple implementation of the buffer-access as seen from the operating-system. The common base of collision-free and locking-free access with two asynchronous partners is the three-buffer structure. Figure 1 shows the connection between two processors at the hardware-level and the location of the buffers for the communication.

<table>
<thead>
<tr>
<th>Type</th>
<th>BufferIndex = (Buffer1, Buffer2, Buffer3);</th>
</tr>
</thead>
<tbody>
<tr>
<td>Var</td>
<td>Actual, ReadLocked (may only be written by the producer)</td>
</tr>
<tr>
<td></td>
<td>may only be written by the consumer</td>
</tr>
<tr>
<td></td>
<td>: BufferIndex;</td>
</tr>
<tr>
<td></td>
<td>{ Both variables has to be one byte long and }</td>
</tr>
<tr>
<td></td>
<td>{ are located in the dual-ported-RAM area. }</td>
</tr>
<tr>
<td></td>
<td>{ The initial value of both variables should be &quot;Buffer1&quot;. }</td>
</tr>
</tbody>
</table>

**Figure 2:** Common data-structures

**Figure 3:** Buffer-access for reading

**Figure 4:** Buffer-access for writing
Figure 2.3 and 4 are the implementation fragments (in a
Pascal-like syntax) for reading from and writing to the
communication-area. The critical accesses to the variables
"ReadLocked" and "Actual" are marked (Bold for a critical
writing; italic for a critical reading).

Variables not under local control may change their values
at any time. i.e., before you may assign the read value (i.e.,
of "Actual") to your local parameter, the value may have
changed! This fact seems to make any formal proof of the
correctness quite hard. Fortunately there is only a small
number of values, the critical variables may have changed
to. So it is possible to proof all the combinatorial cases step
by step.

To assure the correctness of the whole realtime-transfer you
have to proof the following four points in detail.

a. Collision-free
The producer has to select a buffer (in phase 1) which
can not be used from the consumer during the whole
writing-access (phase 2).

b. Definite results
The producer as well as the consumer selects always ex-
actly one of the three available buffers.

c. Termination
The access-routines for the producer as well as the con-
sumer have to be finished after an exact predefined
time. This fact is trivial for the producer, but for the con-
sumer a closer look is needed. The while-loop of the
consumer is at most being executed two times, with the
following exception: The consumer itself is much too
slow, i.e. phase 1 of the consumer is executed slower
than phase 1, 2 and 3 of the producer (this includes se-
lecting a buffer and writing of the whole buffer). This
limitation is tolerable, because first you are getting the
actual buffer in any case, and second if the consumer is
late for some reason (a long interrupt handler, or some-
thing like that) the extra loop does not mean a long
latency in relation to the time being spent in the in-
trrupt handler.

d. Actuality
The consumer gets a buffer which is, at the time of se-
lecting the buffer, as actual as possible.

Up to here, only the access-routines at the operating-sys-
tem level are mentioned. But how does this appear to the
task? The syntax is really simple and the semantic is much
like an electric wire. There are two special functions for
each variable, so all the possibilities of range- and type-
checking may be used.

For a consuming task the interface is shown in the follow-
ing:

    LookForNew <VarName> (Var <VarName>: <VarType>): Boolean;

as an example:

    LookForNewRadarMap (Var RadarMap: RadarShot): Boolean;

The boolean result signals the actuality of the read infor-
mation (is this information ever being read before?).

For a producing task the functional interface looks like this.

    Make<VarName>Available (Var <VarName>: <VarType>);

as an example:

    MakeRadarMapAvailable (RadarMap: RadarShot);

As the final remark for this chapter once again we would like
to emphasize that reading or writing in this communi-
cation-scheme is free of blocking even when the communi-
tcation partner has crashed in a critical phase!

3.2. Higher communication levels

The above described realtime-transfer mechanism is well
defined and easy to use. Theoretically this scheme is suf-
cient to construct a multiprocessor system. If you are going
to design a practical system, you would not be satisfied
with this kind of transfer. Well, actuality is a nice feature,
but what about the "conventional" transfers with flow-
control and error-reports?

So there is a need for two additional communication layers,
not replacing the realtime-ports, but adding some more
functionality in case you need it. In the rest of this chapter
we will try to give a short overview of the higher commu-
nication levels. It is not necessary to describe the protocols
in detail, most of them are well known.

The first layer is called message-ports, and the main func-
tionality is flow-control, i.e., keeping order in a queue of
packets, not destroying old information. For this purpose
two realtime-ports are used (one for each direction). For
the task the message-ports are as easy to use as the realtime-
ports, but with a quite different semantic. You might con-
sider the message-ports as a kind of pipelines in a UNIX-
like world.

The second layer introduces some functionality for sending
instructions from one task to an other and for controlling
the execution. So you have flow-control and execution-con-
trol in this layer of the communication. Regarding this pro-
col it is useful to talk about clients and servers instead of
readers and writers. The server has to give a report at two
points in the communication-scheme. First when it gets an
new instruction, and second when the instruction is exe-
cuted (successfully or with an error-message). The transfer
and the execution of the instructions may overlay, so the
server may accept a number of instructions, before it re-
ports the first execution. A server can be used by several
clients, but the instructions stored by the server must be-
long to the same client. Before a new client appears to the
server, all the old instructions have to be completed.

3.3. Need for a communication-
controller

Theoretically one might think of a realisation of the struc-
ture from figure 1 in form of one motherboard being
equipped with both processors and the dual-ported-RAM.
But it does not seem to be the practicable version, when
you think of about one or two dozen processors in the
whole system. In a real system one processor (or a small
number of processors) will be implemented on one board.
So one of the communication-partners can only access the dual-ported-RAM via some kind of communication-system (normally a short range bus-system). This means a break in the realtime-communication scheme shown so far, because the communication is not symmetric at the physical level. One processor may access the dual-ported-RAM much like the local RAM, while the other processor has to use a communication system to access the same dual-ported-RAM.

A new aspect appears from here on. What happens if the access to the (far) dual-ported-RAM fails, because of a disturbance on the communication-system? In the above discussion a memory-access was a local transfer and therefore without any aspects of a failed communication.

With this problem in mind we are running into a contradiction. On the one hand it is necessary to finish a transfer in a short predefined time, but on the other hand a failed access via the communication-system must be repeated. The processor for the local task is not available any longer after the first failed trial. So which processor will initiate the second trial?

The problem can only be solved by introducing a third processor as a host for the communication-controller as shown in figure 5.

From the view of the tasks any buffer-access looks like an access to the local RAM, i.e. it can be successfully done in a well defined time. The communication-controller may read from or write to the (far) dual-ported-RAM several times, without disturbing the local tasks at all.

There is not an immediate connection between the buffer-areas of the single tasks any longer, but the communication-controller may guarantee that the transfer from one buffer-area to the other will be done with an adequate frequency. For the useful definition of this frequency see chapter 3-4 "Cyclic transfers".

There are some additional functions a communication-controller may offer. If an information is useful for a number of consumers the communication-controller may distribute this information in the manner of a simulated broadcast. Notice that the pure realtime-transfer from chapter 3-1 is not able to distribute information - it is limited to point-to-point transfers. It should also be possible to combine the output of several producers on one "multi-producer-channel" (of course they should produce the same kind of information).

One of the most important arguments for a communication-controller is the fact that a common communication-system must be arbitrated. Thinking of a really distributed communication-scheme - i.e. there is a number of different senders - each sender has to complete an (bus) arbitration-cycle before any communication may take place. The actual duration of one arbitration phase is principally indeterminable, there is only an upper limit (if the arbitration mechanism is “fair”), so it is quite difficult to calculate the worst case in such a system.

If there is only one participant (the communication-controller) which has to fulfill all the transfers, it may occupy the communication-media all the time. This means there is no arbitration at all and the communication-system shows a deterministic behaviour.

Another aspect is the centralized functionality. Is the centralized communication-controller a security-risk for a distributed system, i.e. what happens if the communication-controller fails, for some reason? In case that the dual-ported-memory-areas are organized in a symmetric way, each processor may play the role of the communication-controller. Further you may reserve an extra processor-system which may detect a breakdown of the bus-transfers and fulfil the communication-tasks if the main communication-controller is failed.

If you are only interested in a graceful shutdown of the system, it is not necessary to implement an extra communication-controller, but it is enough to offer a common emergency-interrupt.

3-4. Cyclic transfers

Cyclic transfers means that there is a pre-scheduling of the communication-slots instead of transient transfers while the system is running. The pre-calculated scheduling plan is then executed in a cyclic manner. For an efficient resource usage it is necessary to allow only powers of two
from the highest frequency (i.e. the smallest time-slot) in
the system.
We will highlight the aspects of this kind of transfer in the
form of three questions.

What is the major problem with transient transfers?
Whenever a producer wants to distribute its results (this
happens completely asynchronously) it runs through an
arbitration-phase on the communication-system. It is quite
difficult to calculate the time, the process has to spend in
this phase. The only way to overcome this unsure timing-
knowledge is to hold out enough computational and com-
munication resources. If you are forced to guarantee some
realtime-features, this resources may become quite large.

What is the restriction to pre-scheduling?
The restriction is really simple - you have to know the max-
imal communication times in advance. In a realtime sys-
tem the worst case conditions must be calculated. This should
be possible, if you want to assure reliability of the whole
system. From the worst case conditions you have to deduce
the highest needed sampling frequency. This frequency is
the smallest time-slot on the communication-system. All
other transfers must occur as a multiple or (better) as a
power of two of this smallest time-slot.

What are the advantages of a cyclic-transfer-system?
The construction is based on worst case conditions, i.e. the
worst case may happen without any confusion. Additionally
it is possible to do something more, a kind of over-sam-
pling. If the maximal needed sampling frequency is
known, three possibilities are implied here. First the com-
munication-system is not able to transfer data with such a
frequency. Then you have to look for some quicker hard-
ware, or you have to relax your realtime-constraints. Sec-
ond, the communication capacity just corresponds to this
highest frequency, so congratulations for the department.
But the normal case should be, that there is
some extra capacity of the communication-media, even in
the worst case. In this context worst case means, the con-
straints of the physical system are considered, but all the
computer hardware is assumed to be without any failure,
especially the communication-system. So why not using
this extra capacity for a number of redundant transfers? In
a physical environment this may be interpreted as over-
sampling. From the computer scientist's point of view this
means we are using these extra resources for redundancy.
The best we can do to avoid the risk of transient failures, is
to use all the communication-capacity for as much redu-
dant transfers as possible.

4. ...have a closer look at some gen-
eral aspects of ALBATROSS
In this chapter we will highlight two, a little bit more gen-
eral aspects which are not necessarily or directly deduced
from realtime-constraints. These are an easy way to keep
our operating system flexible and a construction to get an
insight into the running system. There is a much longer list
of features, but most of them are conventional implemen-
tations and so, outside the scope of this article.
Of course the way to handle interrupts and operating-sys-
tem-traps is a critical point in any realtime-system, but
there are only a small number of possibilities to get a quick
response. Further these conventional implementations are
extremely processor-dependant, so there can not be a gen-
eral strategy, but only concrete versions for each processor.

4.1. Flexibility
We are using a quite simple way, to keep the operating-sys-
tem able to adapt on a large range of several hardware-en-
vironsments. The common hardware on all the allowed
processor-boards must be a member of the 680x0-family
and a dual-ported-RAM connected to the communication-
system (for instance via VMEbus). All other components
are declared in a special range of the ROM-area, the har-
dware-description. Each instance of the operating-system is
carrying the whole range of drivers for all allowed control-
ers and interfaces. While starting up the system, the oper-
ating-system checks the hardware-description and installs
the associated test-routines and drivers.
For the operating-system itself there are three different
sources. It can be loaded from the local ROM (if it was be-
ting tested and tested and tested) or from the local serial-
controller or via the communication-system from another
processor-board which has already a version of the operat-
ing-system available. So the operating-system is self dis-
tributing - a nice feature in a test-environment in which the
operating-system has to be updated quite often.

4.2. Keeping on-line in a running
system
Assuring some realtime-features for the single task, is a
necessary step in the design of a whole realtime-system,
but it is not sufficient. You have to think about a possibility
to monitor the tasks running under realtime-constraints.
The critical point is to have a look inside the running sys-
tem without disturbing someone. It is obvious that there
may not be an explicit or implicit stop-command, when ob-
erving the system.
Assuming that the needed information is being transferred
sometimes via the communication-system - there is a sim-
ple, but perfect solution for this problem.
All the information on the communication-system has to be
stored temporary in the local memory domain of the com-
munication-controller. Assuming further that the local
memory domain is large enough and can be shared with an
other task - the supervisor. The communication-controller
can store the transferred packets in the manner of a cyclic-
connected list. The supervisor may also access the area of
this cyclic-connected lists, so it is able to read all the com-
munication packets, without any side-effect for the whole
system.
Of course, usually it is not useful to read all the transferred
information, because the user-interface is too slow to show
the data in realtime, but you might think of three modes the
supervisor can give useful information to the user.
First, when the system is running at full speed, the user
5. Conclusion

Finally we will give a short collection of the main strategies used in ALBATROSS.

a. Worst case as normal case
Calculating of the worst case conditions, as given by the outer world. These conditions deduce a highest sampling frequency needed for the control of the physical system.

b. Dividing the problem
Splitting the whole problem in a number of (to a certain degree) independent tasks, synchronized via the flow of data.

c. Pre-Scheduling of the communication phases
Generating a pre-calculated (i.e. not calculated at the runtime) scheduling-plan, based on the known highest sampling frequency and the available capacity on the communication-media, using redundancy, i.e. oversampling.

The following features must be offered by the operating-system, to assure the exact execution of the scheduling-plan.

- Locking-free shared buffer management
- An explicit communication-controller

Summarising the realtime-aspects as shows in this article, the key to realtime reliability seems to be the communication-scheme. So perhaps the often mentioned interrupts responding times are not the whole truth in a realtime-world.

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