

# RACE

## building airspace simulations faster and better with actors

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**Abstract**—Creating large, distributed, human-in-the-loop airspace simulations does not have to take armies of developers and years of work. Related code bases can be kept manageable even if they include sophisticated interactive visualization. Starting such projects does not have to require huge upfront licensing fees. We showed this by using contemporary internet software technology.

Our *Runtime for Airspace Concept Evaluation* (RACE) framework utilizes the *actor* programming model and open source components such as *Akka* and *WorldWind* to facilitate rapid development and deployment of distributed simulations that run on top of Java virtual machines, integrate well with external systems, and communicate across the internet. RACE itself is open sourced and available from <https://github.com/NASARace/race>.

### I. INTRODUCTION

#### A. Use Case

Imagine having to build a simulation that imports live data feeds such as real-time ADS-B aircraft positions, transmits these live contacts to an existing, interactive flight simulator, receives back the simulated aircraft positions, and displays all flights on several distributed geospatial viewers that can be synchronized in terms of eye position and selected information.

Imagine further that once you have built such a simulation, requirements are extended to include import of live flight, weather and airport data for the whole *National Airspace System* (NAS) through FAA's *System Wide Information Management* (SWIM [1]) servers, which can easily exceed 4000 live flights at any given time. Moreover, all this data has to be recordable in order to replay it off-line for further analysis, or overlay it to live simulations at a later time.

This is not a hypothetical use case - it was one of the motivating examples for the development of RACE, and it took less than 15,000 lines of platform-independent code to implement. The remainder of this paper describes how this was achieved, and how the resulting system can be further extended.

#### B. Targeted Application Properties

Dissecting the above use case, several aspects of the targeted application domain stand out:

(1) The resulting applications are *event based*, they are reacting to external stimuli of different sources, formats and communication channels.

(2) Applications can be *Live, Virtual or Constructive* (LVC) simulations. The system has to accommodate humans in the loop by means of interactive components and external connectivity. For constructive simulations, applications should support time scaling.

(3) Applications typically incorporate existing, external systems such as live data feeds and specialized simulators. External systems are supposed to be used *as-is*. Adaptation has to happen within the application components, not the external system.

(4) There is no fixed set of application components, hence the application framework has to support efficient development of new components without having to change the existing code base. This especially calls for a component model that is sufficiently understood and documented.

(5) Applications should be configurable in terms of component types and component interactions (communication). Application components should be generic to support configuration.

(6) Applications can be massively concurrent, hence the framework they are built with has to free component developers from the burden to do explicit synchronization and scheduling, which are notoriously difficult tasks.

(7) Applications can be distributed, for reasons of scalability and access to local resources such as hardware simulators. Consequently, the component model should provide location transparency, i.e. should allow the user to configure where a component runs without having to change its implementation.

(8) Most applications require specific visualization, hence the application framework has to provide an extensible geospatial viewer infrastructure. Extensions can be related to new data channels, rendering methods, and user interactions.

(9) RACE applications are (mostly) simulations; its components and the system as a whole have to be deterministic. Similar input should produce similar results.

(10) Last but not least, everybody should be able to build RACE applications, hence the underlying framework should be open sourced, and its core should only depend on open sourced third party libraries.

## II. BACKGROUND - ACTORS

Most of the aforementioned properties depend critically on choosing a suitable *programming model* for application components, which is the basis and starting point for our discussion of RACE.

*Actors* are a model of concurrent computation that fits well into the outlined application domain. The basic idea is that resulting systems are homogeneously composed of a potentially large number of concurrently executing objects which only communicate through asynchronous messages and don't share state—the actors.

The concept of actors dates back to 1973 [2] and has been a research focus ever since. Actors became subject to numerous scientific publications, including work on formal semantics [3] [4], and as a consequence are now among the best understood computational models for concurrency.

Actors do not exist in a vacuum, they do need an underlying runtime. Arguably the most prominent implementations so far have been in *Erlang* [6], which integrates actors right into the language, and in *Akka* [7]—a framework that is implemented in *Scala* [8] and runs on Java Virtual Machines (JVMs). Both have seen extensive use in large scale production systems, ranging from phone switches to web applications to cluster computing.

We chose Akka as the actor basis for RACE since we wanted to utilize the vast third party infrastructure that is available for JVMs. As shown in Fig. 1, Akka actors have three essential features:

- a system provided *actor reference* (handle) that is used to send messages to this actor,
- a system managed *mailbox* that hold messages received by this actor,
- a user provided *message handler*.

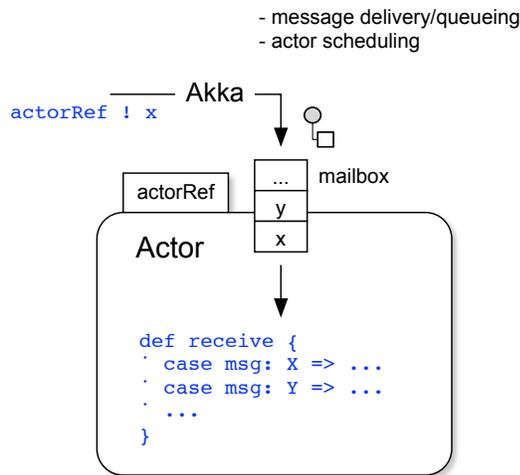


Fig. 1. actor features

Within each actor, processing of messages takes place sequentially in the order in which messages were received. The Akka framework guarantees that no actor executes simultaneously in different threads. Actor references can only be used to

send messages, not to access internals of the respective actor. Together, these properties avoid data races—a common root cause of concurrency related defects—which essentially allows an analyst to view the actor implementation as a sequential program.

This is an idealized model that only holds under the caveat that no shared mutable object is passed into an actor constructor or is accessible through messages, which is why Scala as a (functional) programming language with emphasis on immutable data is our language of choice for RACE implementation.

Akka actors require remarkably little overhead, a basic definition can be as simple as

```
import akka.actor.Actor

class MyActor extends Actor {
  def receive = {
    case msg => sender ! "got_it"
  }
}
```

Akka actors can communicate in two different ways:

- point-to-point—a message is explicitly sent to the receiving actor,
- publish-subscribe—the receiving actor registers its interest about a certain topic on an Akka *EventBus*, and the sender publishes messages to this bus without having to know about its subscribers.

Akka supports both communication types. For point-to-point communication, this includes full location transparency, i.e. messages can be sent to actors running in different processes. For publish-subscribe, there needs to be additional infrastructure to achieve seamless *remoting*, which is provided by RACE on top of Akka and is the subject of the next section.

## III. RACE DESIGN

Since RACE applications are composed of actors, RACE leans heavily on Akka as its implementation basis. However, Akka actors are intentionally application agnostic whereas RACE has a number of additional requirements and hence—among other features—adds support for

- fully runtime configurable systems,
- deterministic system initialization and termination,
- network enabled publish-subscribe mechanism with on-demand data flow control,
- geospatial visualization by means of the *NASA World-Wind* [11] viewer.

The remainder of this section will give a high-level overview of the RACE design and then look at each of these topics separately.

### A. Anatomy of a RACE System

As depicted in Fig. 2, the starting point to understanding the RACE anatomy is a configuration file that specifies which actors participate in a RACE application, and how these actors connect to each other. Configurations are text files that are created outside of RACE.

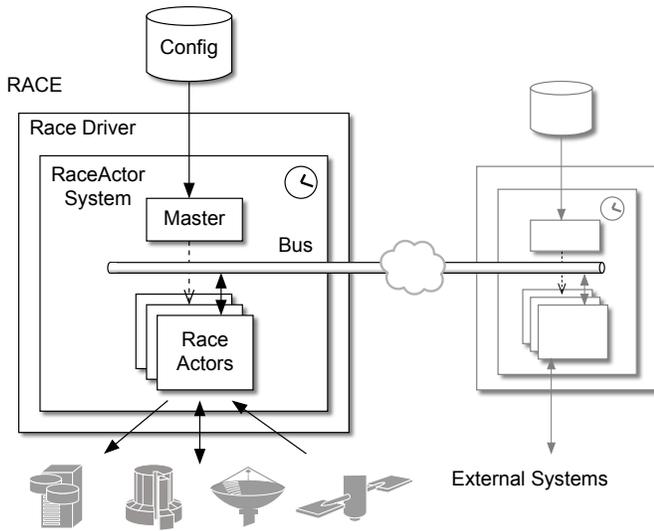


Fig. 2. RACE overview

The top-level runtime component is the **RACE Driver**, which is usually the main class of a respective application and directly invoked by the user. There are several driver variants depending on user interface and locality, but all share the same set of basic functions:

- 1) select/acquire the contents of a configuration file and translate it into a configuration object,
- 2) instantiate a *RaceActorSystem* with this configuration object,
- 3) start, query and terminate this *RaceActorSystem* based on user commands.

The **RaceActorSystem** aggregates the following objects: the *Master* actor, the *Bus*, a *Clock*, and any number of configured *RaceActors*.

Upon instantiation by the driver, the *RaceActorSystem* creates the *Master*, the *Bus* and the *Clock*, and then passes the configuration object on to the *Master* actor.

The **Master** actor is responsible for creating and then supervising the configured *RaceActors*, providing the sub-configuration for each particular actor as the sole constructor argument. There are four distinct phases of control executed by the *Master*:

- 1) creation of configured *RaceActors*,
- 2) dynamic initialization of created *RaceActors*,
- 3) start of initialized *RaceActors*,
- 4) termination of started *RaceActors*.

Each phase is only entered after the preceding one has been completed. Within each phase *RaceActors* are processed sequentially based on their configuration order, i.e. each actor can rely on all preceding actors having successfully completed the respective phase.

The **Bus** is merely a wrapper around an Akka *EventBus* that implements a network enabled publish-subscribe mechanism as the primary means of *RaceActor* communication.

The **RaceActors** finally are the application specific components, performing tasks such as importing from external data sources, translation and filtering of imported data, visualization, analysis and more. Most *RaceActors* do so by subscribing and publishing to *Bus* channels they obtain from their configuration data.

*RaceActors* are also the means to communicate with other RACE processes. By specifying the location (URL) of a *RaceActor* in the RACE configuration, such remote actors can be seamlessly integrated into a RACE application, using normal *Bus* channels for communication without the need of any remoting-specific user code. Remote actors can be looked up (in case they have to be started locally) or instantiated remotely.

Based on this connectivity, it is possible to build whole topologies of interacting RACE systems.

### B. Configuration

RACE applications are not hard coded, they are configured by means of text files that specify which *RaceActors* partake in a simulation, and what parameter values these actors should be initialized with. The preferred format for configuration files is *HOCON* [10], which is a *JSON* [9] dialect that is focused on readability.

The underlying data model is a tree of key-value elements. Each element value can be either a primitive (String, Boolean, Int etc.), an object (set of key-value pairs “{..}”) or an array of element values (“[..]”). Figure 3 shows basic structure, elements and connections of RACE configuration files.

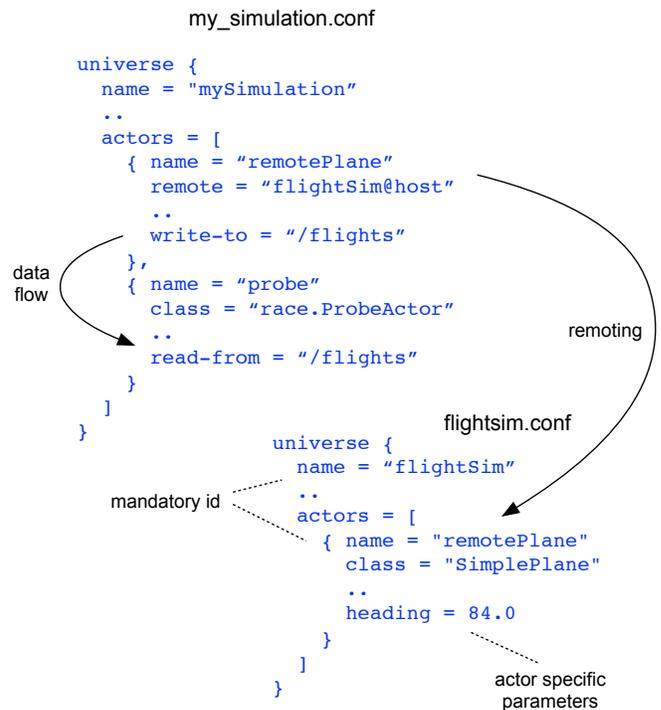


Fig. 3. RACE configuration

The top level element of a RACE configuration file is a `universe` object, which contains two main sub-elements:

- a name that identifies this RACE instance so that it can be referenced by other RACE processes,
- an `actors` array that specifies which `RaceActors` are part of this RACE instance.

Each `actors` element specifies a single `RaceActor`, identified by a mandatory `name` element. Actors that are created by this RACE process also need to have a `class` element holding the respective class name. An optional `remote` element indicates this is a remote actor running on an external RACE system. Actors can also be marked as optional, in which case a failed lookup or creation does not terminate the RACE initialization.

`RaceActors` that communicate through `Bus` channels have `read-from` and `write-to` configuration elements, which hold either single channel names or an array thereof. Channel names are strings that should use a path-like convention. Channels do not need to be defined separately.

In addition to such system elements, each `RaceActor` can have any number of actor type-specific parameters. Values starting with a “??” prefix are used as keys to look up sensitive configuration data (e.g. user credentials) in an optional `vault`, which is a secondary configuration file that is encrypted. Vaults have to be specified during RACE startup, require symmetric keys, and are never stored as clear text during execution.

Conceptually, RACE configurations use a declarative language to define a directed graph in which `RaceActors` represent the nodes, and `Bus` channels represent the edges. The resulting graphs do not need to be acyclic.

RACE configurations contain more information than just type and connection of actors—the order in which actors are specified does matter. The Master actor creates, initializes and starts `RaceActors` strictly according to this order, and terminates them in reverse order. In each phase, an actor can depend on previous actors having completed the respective phase.

### C. RaceActors

`RaceActors` are Akka actors which are initialized from RACE configuration data, and implement a RACE-specific state model. This state model closely follows the different lifetime phases of a RACE system:

- 1) creation,
- 2) initialization,
- 3) run (including suspend/resume),
- 4) termination.

The distinction between the creation and initialization phases becomes obvious when looking at RACE instances that communicate through remote actors. While a remote actor might get instantiated by the remote RACE system ahead of time, it still needs to be initialized with data (e.g. `Bus` channels) that integrate this actor into the local RACE system.

Since *location transparency* is an explicit design goal for `RaceActors`, we do not introduce a different state model for

remote actors, but call out dynamic initialization as a separate step. This has the added benefit that those local actors needing initialization from other actors can make use of the same state model; this avoids actor-pair specific protocols.

Figure 4 shows the basic `RaceActor` states and transitions.

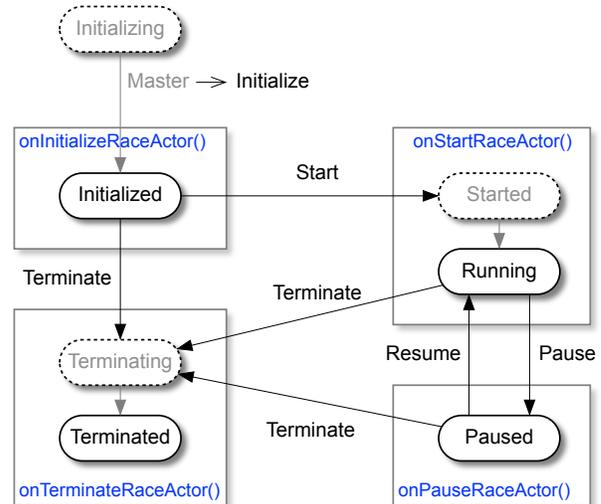


Fig. 4. `RaceActor` States

Each of the `RaceActor` state transitions is initiated by the Master and mapped into a function that can be overridden by the concrete actor class, which mixes in one or more of the system-provided `RaceActor` traits. The reference transition sequence is as follows:

$\circ \rightarrow$  *Initializing* : the initial transition is triggered when the Master instantiates a `RaceActor`, and is implemented by means of its constructor chain. This usually includes static (context-free) initialization based on the local actor configuration object which is the sole constructor argument.

*Initializing*  $\rightarrow$  *Initialized* : this transition is triggered when the Master sends the *InitializeRaceActor* system message that is mapped by the system into a `onInitializeRaceActor()` call. The purpose of this method is to perform context-aware initialization based on a (possibly remote) configuration object that is part of the message. This especially includes subscription to configured `read-from` `Bus` channels. After `onInitializeRaceActor()` returns, the system activates the actor-specific `handleMessage()` method as the default message handler.

*Initialized*  $\rightarrow$  *Running* : this marks the beginning of the simulation in response to a *StartRaceActor* system message sent by the Master, which is mapped into an `onStartRaceActor()` call. Typical reactions include the start of data publishing.

*Running*  $\rightarrow$  *Terminated* : the final transition is triggered by receiving a *TerminateRaceActor* system message from the Master, which results in an `onTerminateRaceActor()` call during which data production is stopped and external connections are closed.

If `RaceActors` override an `on<Message>()` method, they should call the respective `super` method from within their implementation to make sure mixed-in system traits function properly.

Although system message callbacks are an important part of a `RaceActor` implementation, the primary feature is usually the `handleMessage` dispatcher which is activated when the actor reaches the *Initialized* state. This dispatcher is a Scala *Partial Function* that pattern matches on the message types and values which are processed by this actor. The reason why this handler is not activated during actor construction is that message processing might depend on fields which are not set before the *Initialized* transition is completed.

The following code snippet shows how system message callbacks and the message handler work together in the context of a simple `RaceActor` example:

```
import gov.nasa.race.core.PublishingRaceActor
...
class Airplane (val config: Config)
  extends PublishingRaceActor with ... {
  val id = config.getString("id")
  var updateInterval = config.getDuration(...)
  var fpos: FlightPosition = ...
  ...
  override def onInitializeRaceActor(...,
                                     conf: Config) = {
    super.onInitializeRaceActor(...,conf)
    fpos = getInitialPosition(conf)
  }

  override def onStartRaceActor = {
    startUpdateNotifications(updateInterval)
  }

  override def handleMessage = {
    case Update =>
      fpos = computeNewPosition(simTime)
      publish(fpos)
  }

  override def onTerminateRaceActor = {
    stopUpdateNotifications()
  }
  ...
}
```

The standard RACE distribution contains a number of ready-to-use `RaceActors` for generic tasks such as Java Messaging Service (JMS) import, XML-to-object translation, content-based filtering and more. While this collection of generic system actors is supposed to grow, development of new, application-specific `RaceActors` is considered to be the primary way to extend RACE and hence explicitly encouraged.

#### D. Bus Channels

Bus channels are the primary mechanism through which `RaceActors` communicate. They implement fully runtime configurable publish-subscribe (1:N) messaging that works seamlessly with remote actors. Each channel is identified by a path-like name (e.g. `"/flights/positions"`), which organizes the channels of a RACE system into a hierarchical name space that allows selection of whole sub-trees by means of name patterns (e.g. `"/flights/*"`). If a channel name starts with a `"/local/"` prefix, respective data will not be sent out to remote actors.

Within a RACE process, Bus channels carry very little runtime costs compared to external messaging systems. Channels do not need to be separately defined, accept arbitrary object references as messages, involve minimal copying, and do not require marshaling/un-marshaling. Within a process, channel messaging approaches the efficiency of function calls with associated context switches.

Bus channels that are used between RACE instances do incur marshaling/un-marshaling costs. While this is transparent to actor code, it shows the same 2-3 orders of magnitude throughput reduction that is typical for external message systems and hence has to be taken into account when partitioning RACE systems.

The RACE Bus is a very thin wrapper around the normal Akka `EventBus`, which already supports sending messages to remote actors, but does not provide the capability for remote actors to publish. This function is added by RACE, using *BusConnector* actors that are automatically created by the Master and passed on to remote `RaceActors` during the initialization phase. When the remote actor publishes a message, under the hood it sends this message point-to-point to the associated `BusConnector`, which then publishes it to the local Bus.

Channel subscription and publishing is mostly implemented in two system traits that can be mixed into concrete `RaceActor` classes: *SubscribingRaceActor* and *PublishingRaceActor*.

During initialization of a `SubscribingRaceActor`, the system automatically subscribes the actor to all channels that were specified in its `read-from` configuration element. Conversely, the system automatically unsubscribes the actor during its termination.

The `PublishingRaceActor` provides a `publish(msg)` method that wraps the message payload into a *BusEvent* that records channel, sender and payload, and then sends this `BusEvent` to the channels specified in the `write-to` configuration of this actor.

Concrete `SubscribingRaceActor` classes then pattern match on the `BusEvents` they process within their `handleMessage` methods:

```
...
override def handleMessage = {
  case BusEvent(channel, x:X, sender) =>
    processXMsg(x)
  ...
}
```

#### E. Channel Topics

If Bus channels are the statically configured pipes through which `RaceActors` send and receive data, *ChannelTopics* can be thought of as the valves that control the data flow along those pipes *on-demand*.

The rationale for implementing the `ChannelTopic` mechanism is that many external data sources are potentially high volume, and do not allow fine grained control over which data they send. Such messages should only proliferate through a RACE system if there are clients that actively process this data, and otherwise should be filtered as close to the RACE system boundaries as possible.

Since a *RaceActor* should only have to know about the channels it subscribes to, and not about which actors publish to those channels, the mechanism has to be fully transitive.

The two traits that implement the mechanism are *ChannelTopicSubscriber* (the requesting consumer) and *ChannelTopicProvider* (the producer). Both define a protocol that works fully transitively and asynchronously, i.e. providers can in turn request their own *ChannelTopics* when they receive a request, and respond once they got their requests answered. A single *ChannelTopic* request can therefore trigger a whole set of (different but related) requests upstream.

Request topics can either be application specific objects, or a system value indicating that a request pertains to the whole channel. It is up to the *ChannelTopicProvider* to pattern match request topics it will serve.

Figure 5 depicts how a *ChannelTopic* request propagates through the system

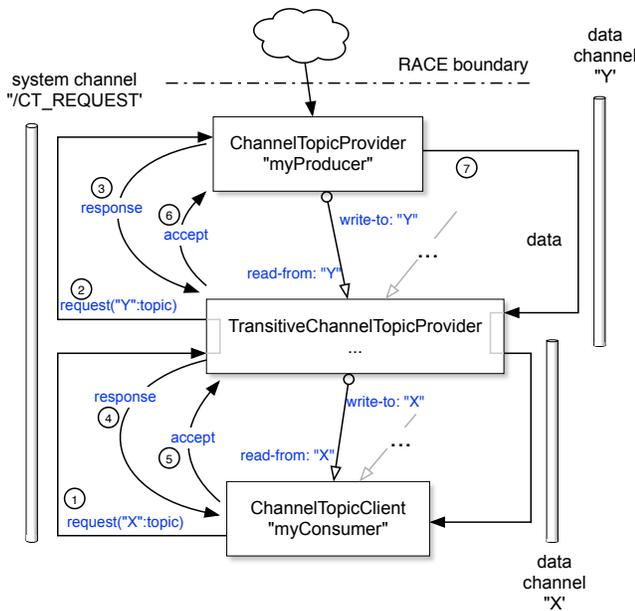


Fig. 5. Channel Topics

At each level, requests are handled in four steps:

- 1) the request itself by the *ChannelTopicSubscriber* actor,
- 2) a response by one or more *ChannelTopicProvider* actors,
- 3) an accept by the requesting actor to the selected provider,
- 4) data publishing of the accepted provider.

Providers that are also requesters can mix in the *TransitiveChannelTopicProvider* trait, which mainly is responsible for mapping incoming to outgoing requests (a 1:N relationship).

### F. WorldWind Viewer

The most visible part of RACE is its *NASA WorldWind* [11] interface. One of the primary use cases of RACE is to visualize large, dynamic geospatial data sets, such as live flight positions within the whole national airspace (see Fig. 7 screen shot).

Respective applications can vary significantly in terms of

- input sources,
- viewport and perspective,
- supported interactions,
- context-aware rendering of objects.

Such complex graphical user interfaces tend to require a large amount of platform-specific code that is expensive to develop and maintain. In addition, most available user interface frameworks are not thread safe, and thus require explicit, error-prone and hard-to-test synchronization between asynchronous data acquisition and user interface (event dispatcher) threads.

RACE includes substantial infrastructure to mitigate these challenges. The centerpiece of this infrastructure is *NASA WorldWind* [11]—an open sourced OpenGL-based [12] geo viewer that runs on all major platforms and can be embedded into Java applications.

Fig. 6 gives a conceptual overview of how *WorldWind* is integrated into RACE.

The primary *WorldWind* concept in the context of RACE is the *RenderableLayer*, which represents a display relevant data set that can be separately controlled in terms of visibility, rendering and updates. RACE uses *RaceLayers* to map its Bus channels into *WorldWind* layers. While a *RaceLayer* executes within the graphical user interface thread, it has an associated *RaceLayerActor* which is responsible for data acquisition by means of RACE channel subscription. Since *RaceLayerActors* execute within Akka threads, they use a dedicated queue within the associated *RaceLayer* to perform the thread-safe handover of display data.

The second, RACE-specific concept is the *UI Panel*, which represents a part of the user interface outside of, but potentially interacting with, *WorldWind*. RACE comes with panels for various tasks such as controlling view positions, selecting layers and displaying information about selected objects. UI panels are collapsible and stacked in a column to the left of the top-level window, whereas *WorldWind* occupies the large canvas to the right of the panel column.

*WorldWind* is incorporated into RACE applications by means of a *RaceViewerActor*, which is just a normal *RaceActor* within a RACE configuration. However, *RaceViewerActors* themselves can be extensively configured with both *RaceLayers* and (less often) *UI Panels*:

```

universe {
  ...
  actors = [
    ...
    { name = "geoViewer"
      class = "gov.nasa.race.ww.RaceViewerActor"
      ...
      layers = [
        { name = "livePos"
          class = "FlightPosLayer"
          read-from = "/live/fpos"
          description = "live_flight_positions"
          ...
        },
        ...
      ],
      ...
    }
  ]
}

```

Just as the *RaceLayerActor/RaceLayer* pairs, the *RaceViewerActor* has a dual in form of the *RaceView* user interface object,

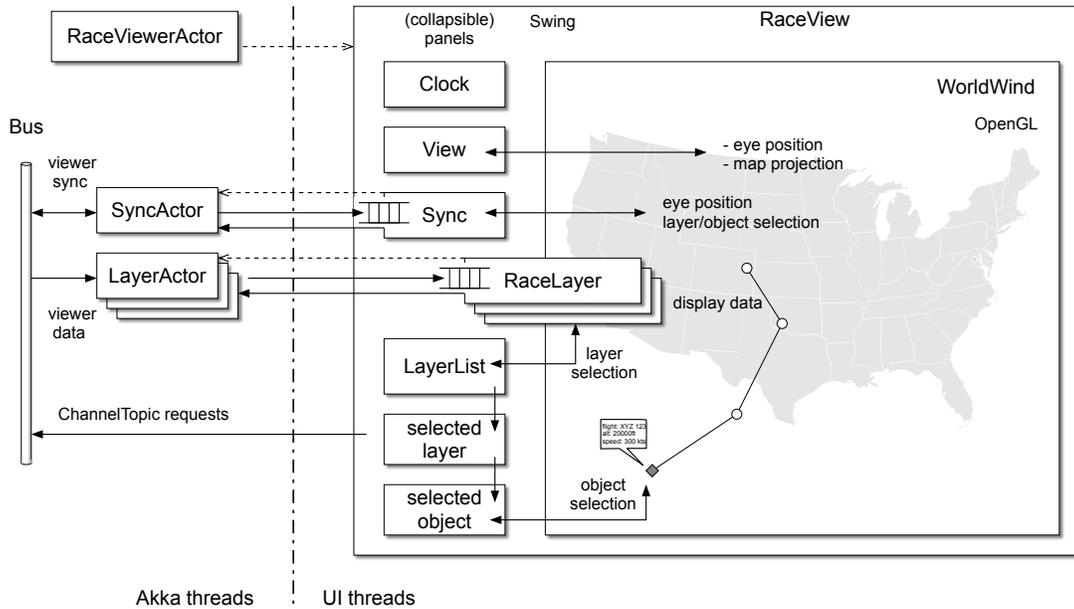


Fig. 6. WorldWind Integration

which is both the aggregation and the mediator between the configured panels and the WorldWind window.

An important aspect of RACE’s WorldWind infrastructure is the synchronization of different viewers. RACE Bus channels can be used for more than just acquisition of display relevant data—they are also a convenient mechanism to exchange viewer state between local and remote RaceViewers.

To that end, the viewer infrastructure includes a *SyncActor/SyncPanel* pair, which can publish viewer changes such as eye position and layer selection to a global Bus channel, and conversely subscribe to this channel to update the local display with remote viewer changes. This type of viewer synchronization is superior to generic, application-unaware screen sharing because it:

- supports fine grained, extensible control of synchronization aspects at the local site,
- is robust in terms of re-synchronization (supports mute and tolerates lost connections),
- lets users dynamically select the remote viewer(s) to synchronize with,
- requires minimal data transfer between viewers (no high volume input events or large images have to be transmitted).

This infrastructure provides a powerful basis to use RACE for applications such as situation rooms: supporting the integration of large screen displays with a variety of controller consoles and without having to resort to expensive and limiting hardware-based solutions.

### G. Other Features

There is more to RACE—several of its current features cannot be discussed in detail within the scope of this paper, and are only briefly mentioned here.

The *RemoteLauncher* infrastructure allows the user to securely start, monitor and control RACE processes through SSH, providing the capability to manage global resources such as configuration files, user ids and gateway access to external servers from one central place. The *RemoteLauncher* especially targets multiple concurrent, automated simulations that make use of dynamic resources such as cloud computing. For security reasons, the *RemoteLauncher* can be configured to run remote RACE instances on login-less accounts. All communication with remote processes is tunneled through SSH, which not only guarantees strong encryption but also simplifies related network configuration.

Many external data sources provide a superset of the required information in the form of pre-validated XML messages. For trusted sources, full schema-based XML translation therefore often results in computational overhead that can be avoided. To this end RACE comes with its own lightweight *XmlPullParser* support that can be more than an order of magnitude faster than comparable solutions, allows convenient extraction of relevant information, and provides full path context for XML elements.

The *XPlaneActor* that is distributed with RACE supports bi-directional communication with the commercial *X-Plane* [13] flight simulator. The *XPlaneActor* uses a normal network socket to send flight positions to X-Plane for cockpit view rendering, and in return receives the position of the simulator plane which can then be displayed with RACE’s WorldWind viewer.

## IV. QUANTITATIVE PROFILE

The RACE distribution currently consists of about 200 source files with 12,500 lines of code (predominantly Scala), not including some test tools to run third party servers.

Roughly a third of this code is related to the viewer infrastructure of RACE. The core itself is the smallest layer with about 1,350 lines of code.

The following runtime data was measured on a 15" MacBook Pro (2.8GHz Intel i7, 16 GB 1600MHz memory, AMD Radeon R9 M370X with 2GB VRAM), running OS X 10.10.5 and Java 1.8.0\_91.

The analyzed RACE application included import of:

- live SWIM Flight Data Publication Service (SFDPS) messages: ~4000 simultaneous flights, ~70 messages/sec,
- live SWIM Airport Surface Detection Equipment, Model X (ASDE-X) messages: ~30 airports, ~30 messages/sec, 50-150 tracks per airport,
- live SWIM Integrated Terminal Weather System (ITWS) precipitation image data: ~80 images, 2-3 messages/sec,
- live Automatic Dependent Surveillance-Broadcast (ADS-B) data, San Francisco Bay Area: ~25 simultaneous flights, 20-40 messages/sec.

All data was received as text messages over a wireless network and was translated into respective objects using load balancing actors. Resulting flight objects and precipitation images were displayed by WorldWind LayerActors.

The viewer was configured to issue ChannelTopic requests when zooming in on an airport providing ASDE-X data, triggering on-demand translation, publication and display of related ASDE-X track positions (aircraft and vehicles) at a 1Hz interval.

The application used 25 actors with up to 13 simultaneously active channels.

The Java process loaded about 8900 classes and executed in up to 81 live threads, using between 200-500 MB of heap memory.

The resulting CPU load averaged below 5% in stable viewer state, and peaked around 20% during garbage collection and viewer interaction. The highest average CPU load of 10% over 10-15 sec occurred during sustained view changes such as zoom and pan operations, identifying graphics as the most computationally intensive task of the system.

The screen shot in Fig. 7 gives an flavor of the involved volume of dynamic data (red dots represent live flights).

This demonstrates that RACE can process a realistic amount and rate of data on commodity hardware, without even having to tap into its potential for massive multi-core architectures and cluster networks.

## V. LIMITATIONS

While actors are a scalable and robust approach for designing massively concurrent and distributed systems, they are not without their own challenges. During our work on RACE we identified a number of topics that should be subject to further analysis.

The preferred *emphmodus operandi* for actors is to restrict themselves to communication through asynchronous messages without sharing state, but sometimes shared memory within a RACE process is the best way to improve performance, reduce redundancy and avoid complex synchronization protocols in

absence of explicit locks. Except for the fact that it might prevent location transparency, shared memory can be a viable design choice, provided that shared objects are immutable during operation. Scala has a strong bias towards functional programming and hence features good support for immutable data (e.g. with its collection library), but it is possible to create data races in Akka actor systems, especially through actor constructor arguments and message fields. This could be mitigated by using targeted static analysis, but so far tool support in this area is limited.

Seamless channel communication by means of remote actors is a powerful tool, but in absence of different APIs it is easy to forget that (a) such communication comes at the potentially significant cost of marshaling/un-marshaling, and (b) some objects might not support marshaling at all, resulting in runtime errors (e.g. for platform specific native objects).

A specific problem of actor systems is detection and mitigation of mailbox saturation, commonly referred to as *back pressure* management. Each actor mailbox is a queue of messages that are waiting to be processed, and if the actor processing does not keep up with the rate at which messages arrive, it can create downstream problems. Since actor mailboxes are Akka system objects (e.g. the required queue synchronization is hidden from user code), detection of back pressure situations might have to resort to test messages that further increase message traffic and hence can aggravate the situation they are supposed to remedy.

Back pressure management (e.g. with dispatcher/worker actor combinations as employed by RACE) is just one example of a broader topic—while it is clear that there are actor patterns, those are not yet as well understood and documented as common software design patterns. Existing literature such as the seminal work of Hohpe and Woolf[5] is mostly focused on the integration aspect of messaging systems in the context of enterprise software.

Last but not least, actors, Scala and Akka are not as mainstream as Java and explicit threading, and thus available workforce is limited. However, the same can be said about most emerging technologies with a high innovation factor.

## VI. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper we have presented the goals and design of RACE—an open sourced framework to build distributed, live, virtual and constructive airspace simulations by means of the *actor programming model*. Reflecting on our work, three conclusions stand out:

- 1) actors do provide the basis for extensibility and scalability that we had envisioned,
- 2) functional programming (Scala) combines well with actors,
- 3) although RACE is still under development, its minimal core together with the maturity of its third party system basis (Akka, WorldWind) already allow applications that go beyond the scope of simple simulations.

From a technical perspective, our immediate plans are to extend the actor collection distributed with RACE, to add more

actor telemetry, and to use RACE in the context of runtime monitoring of future air traffic management models. In terms of adoption and third party contribution, we intend to build an open source community around RACE.

This work is all the more satisfying as we see a lot of potential for future research, ranging from actor pattern analysis to model checking to compositional verification of actor systems. RACE could be exciting for years to come.

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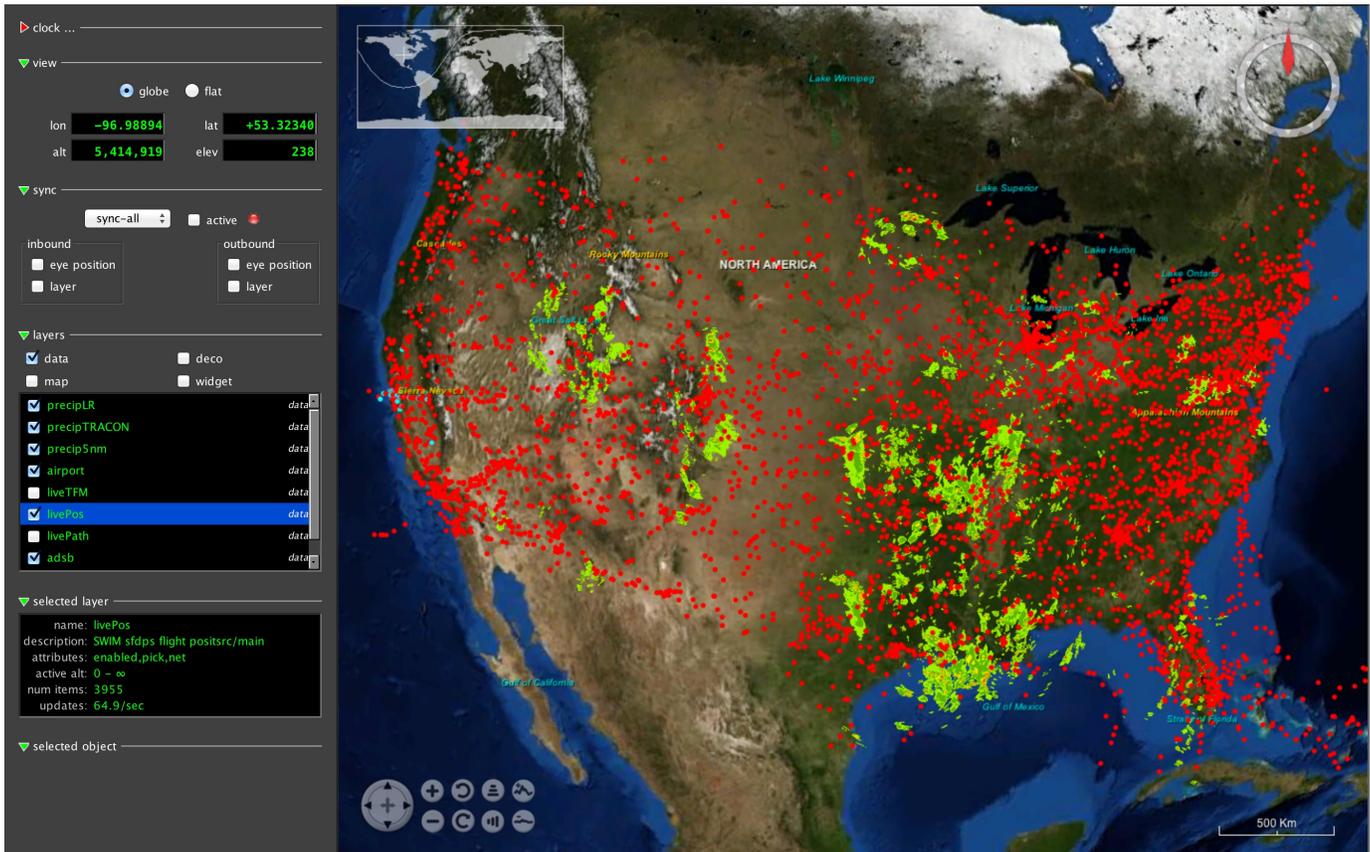


Fig. 7. RACE viewer screen shot