Hippo and GenoM

On the Advantages of Using a Formal-Model Execution Engine
to Control and Verify Critical Robotic System

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and also Anthony MALLET, Reyyan TEKKIN, Mohamed FOUGHALI, Robin VINCELLE, …

SHARC—Software and Hardware Architectures for Robots Control
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Robotic Software

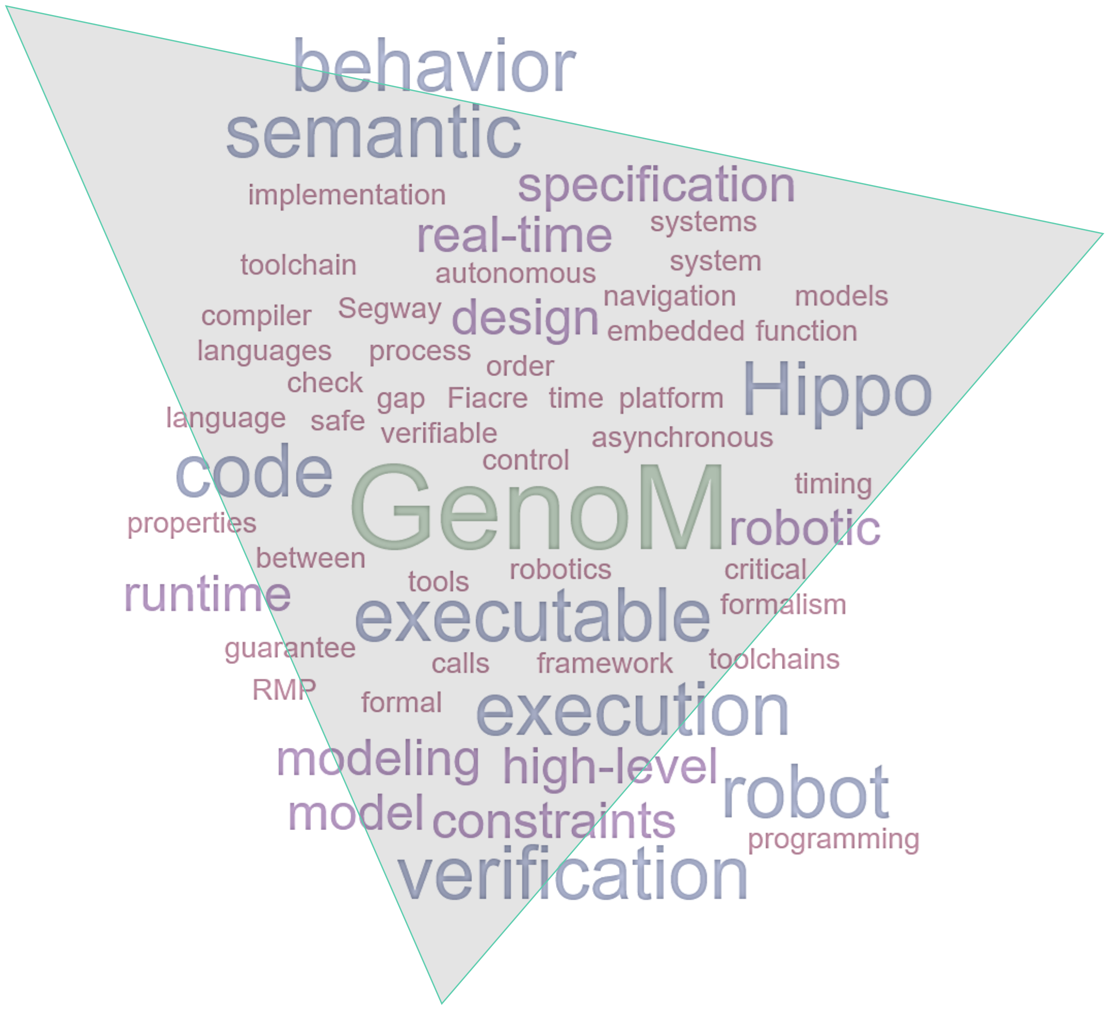
Formal Methods

ROS

GenoM

Pocolibs

Programming Languages



Time Petri nets
Model-checking
Temporal logic (LTL, CTL)

Tina

Process Calculi
Data and Types

Fiacre

Hippo

Schedulability

Functional Architecture; Runtime Systems

A High-Level Overview of GenoM

Formal Methods 101

Formal-Model Execution Engine

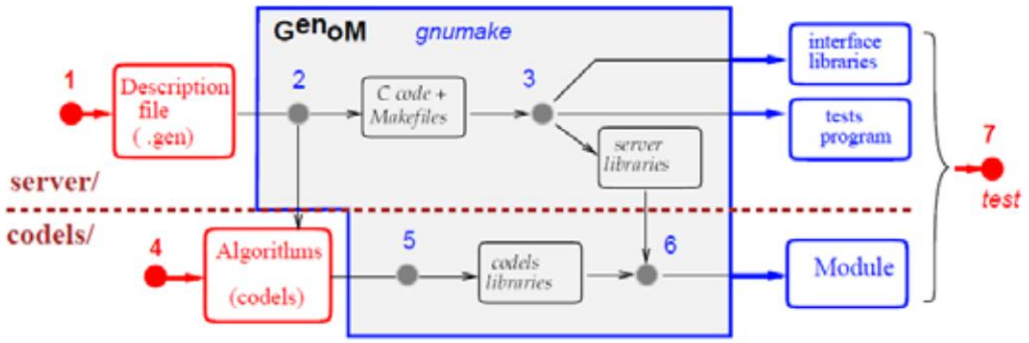
Experimentations

GenoM: Generator of Modules

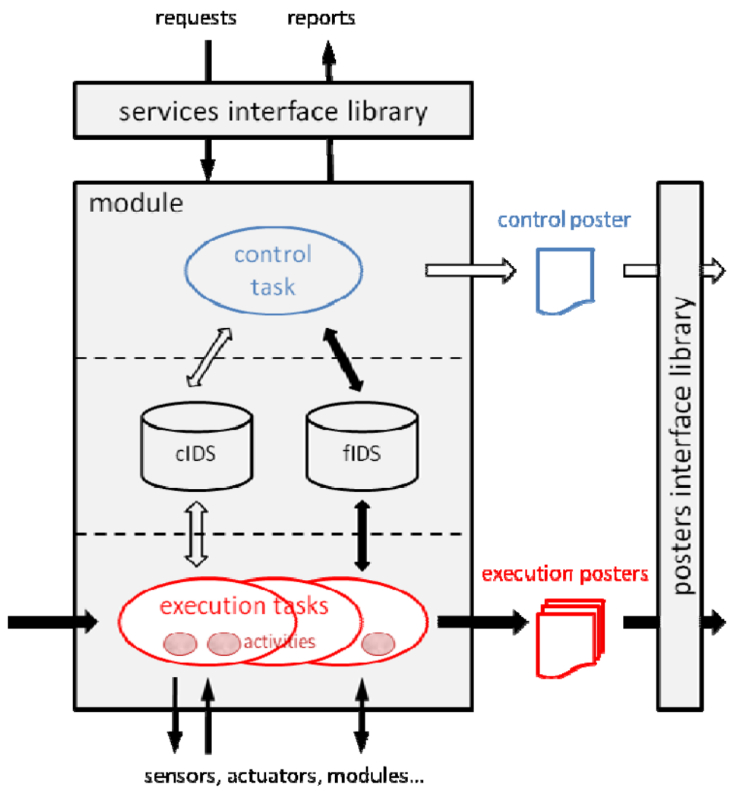
Answer the question: how do you program these ?

Used and developed by the RIS team, at LAAS, for the last 25 years

GenoM (architecture)



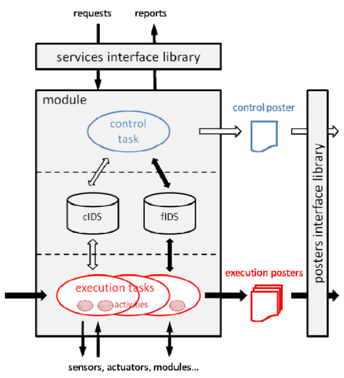
Development cycle

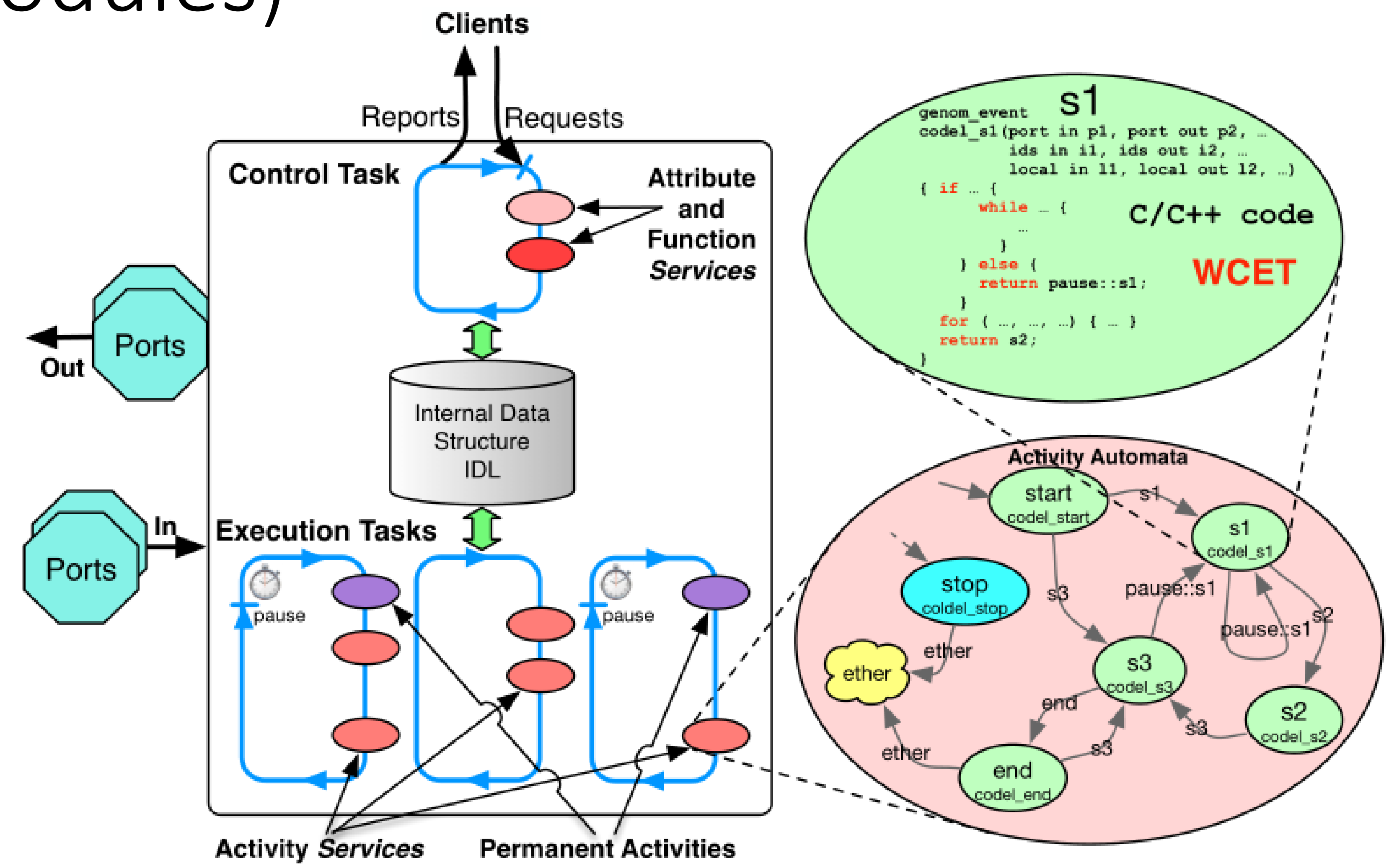


Module structure

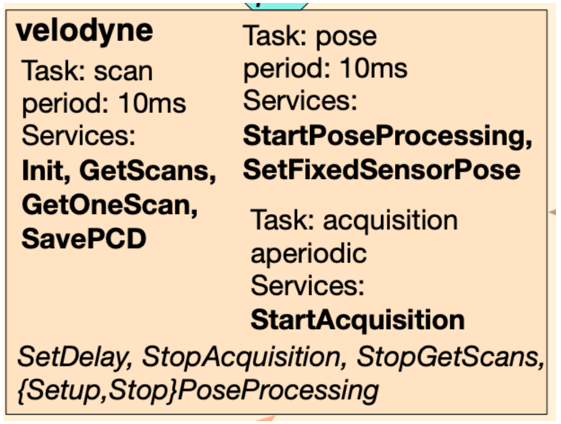
1996

GenoM (modules)





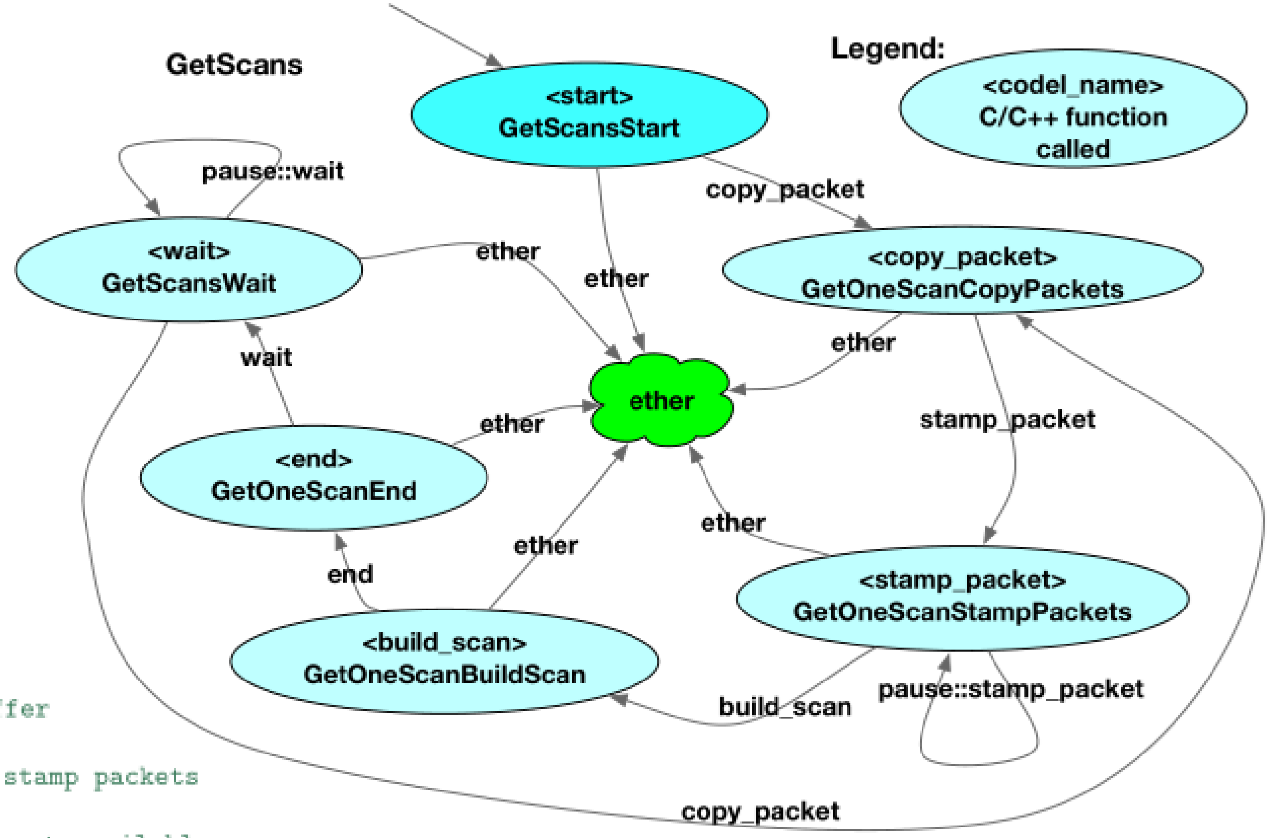
GenoM (code)




```
#pragma require "openrobots2-idl >= 2.0"
#pragma require "minnie-idl"

#include "or/pose/pose_estimator.gen"
#include "mi/sensor/pcl.idl"

component velodyne {
  doc                 "Provides corrected scans from Velodyne sensors.";
  version             "1.0";
  lang                "c";
  email               "felix@laas.fr";
  require             "genom3 >= 2.99.26";
  codels-require      "velodyne-libs >= 0.7", "eigen3", "pcl_common-1.7", "pcl_io-1.7";

  port in  or_pose_estimator::state robot_pose;
  port out or::pcl point_cloud;

  exception e_sys { string<256> what; };
//...
  exception e_port { string<256> what; };

  /* --- ids ------------------------------------------------------------- */
  ids {
    AcquisitionParams acquisition_params; // Acquisition parameters
    PacketBuffer packet_buffer; // Buffer to store time stamped raw packets
    PoseBuffer pose_buffer;     // Buffer to store time stamped pose.
    long fd;                    // file descriptor to get the raw packets (UDP)

    long usec_delay;            // for fault injection purpose to delay port scan writting
  };

  attribute SetDelay(in usec_delay =  1000000)
  {
    doc         "Set the delay in usec we will delay port update (to test the BIP monitor).";
  };

  /* --- acquisition task ---------------------------------------------- */
  task acquisition {
    codel<start>        velodyneAcquisitionTaskStart() yield ether;
    codel<stop>         velodyneAcquisitionTaskStop()  yield ether;

    throws e_mem, e_grabber;
  };


  activity StartAcquisition() {
    doc                 "Starts the data acquisition";
    task                acquisition;
```

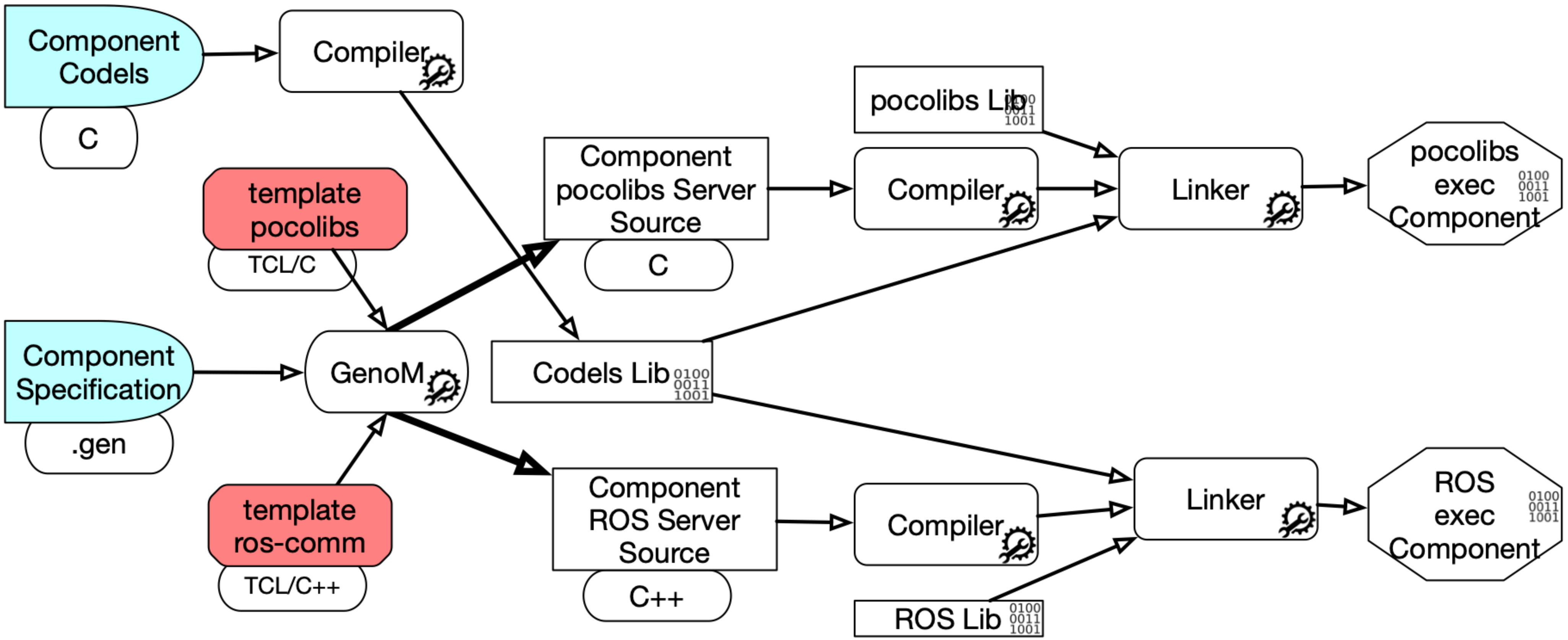
GenoM (code)

```
activity GetScans(
     in double firstAngle = :"First angle of the scan (in degrees)",
     in double lastAngle  = :"Last angle of the scan (in degrees)",
     in double period     = :"Time in between two scans",
     in double timeout    = :"Timeout used when stamping packets")
{
 doc  "Acquire full scans from the velodyne sensor periodically";
 task scan;

 validate GetScansValidate(in firstAngle, in lastAngle, in period);

 codel <start> GetScansStart(in acquisition_params)
             yield copy_packets;
 codel <copy_packets> GetOneScanCopyPackets(in acquisition_params,
                 inout scan_buffer) // get packets from acquisition buffer
             yield stamp_packets;
 codel <stamp_packets> GetOneScanStampPackets(in acquisition_params, // stamp packets
                 inout pose_data, in timeout) // with the proper  pose
             yield pause::stamp_packets, build_scan; // pause:: if pose not available
 codel <build_scan> GetOneScanBuildScan(in acquisition_params,
                 in firstAngle, in lastAngle) // build scan repositioning
             yield end;              // individual packet in the first pose.
 codel <end> GetOneScanEnd(in acquisition_params,
                 port out point_cloud, inout usec_delay) //publish the scan in the
             yield wait;  // point_cloud port. usec_delay is for fault injection.
 codel <wait> GetScansWait(in period) // wait next user defined scan period
             yield pause::wait, copy_packets; // then loop back.

 interrupts GetOneScan, SavePCD, GetScans;
};
```



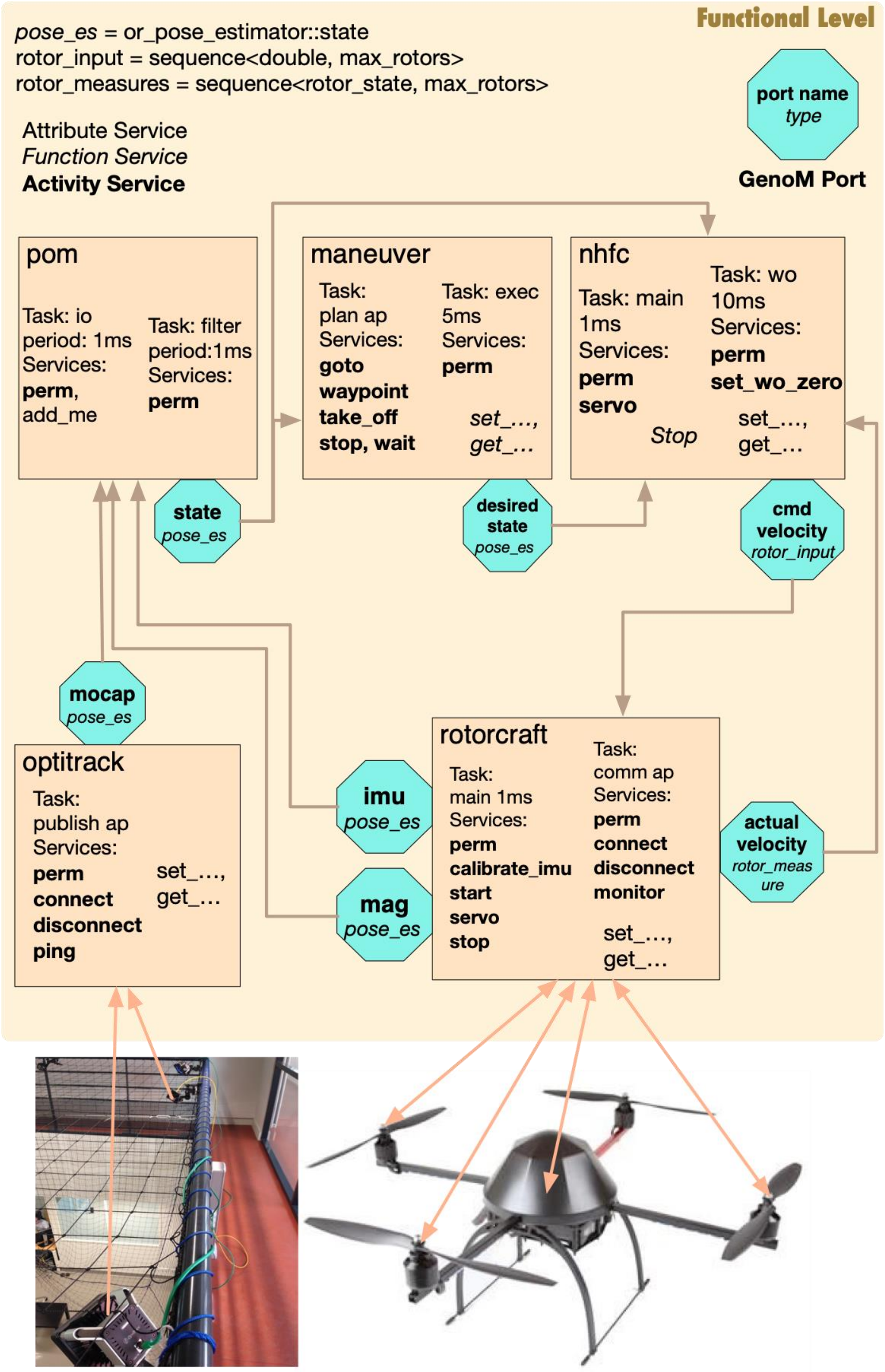
scan task of the velodyne module

GenoM (templates)



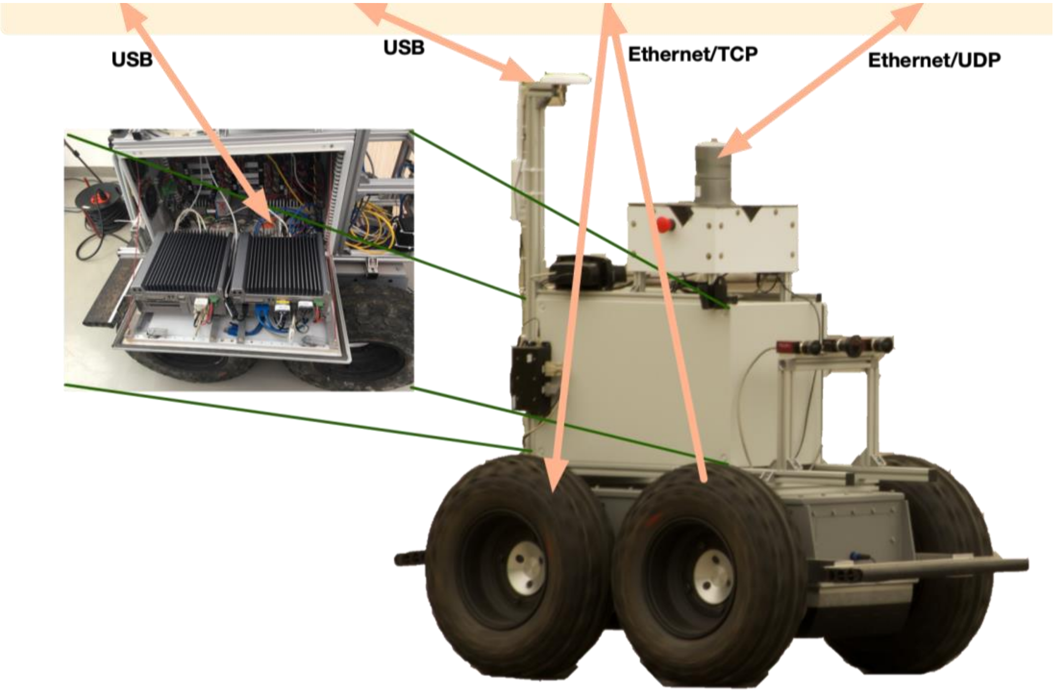
Drone

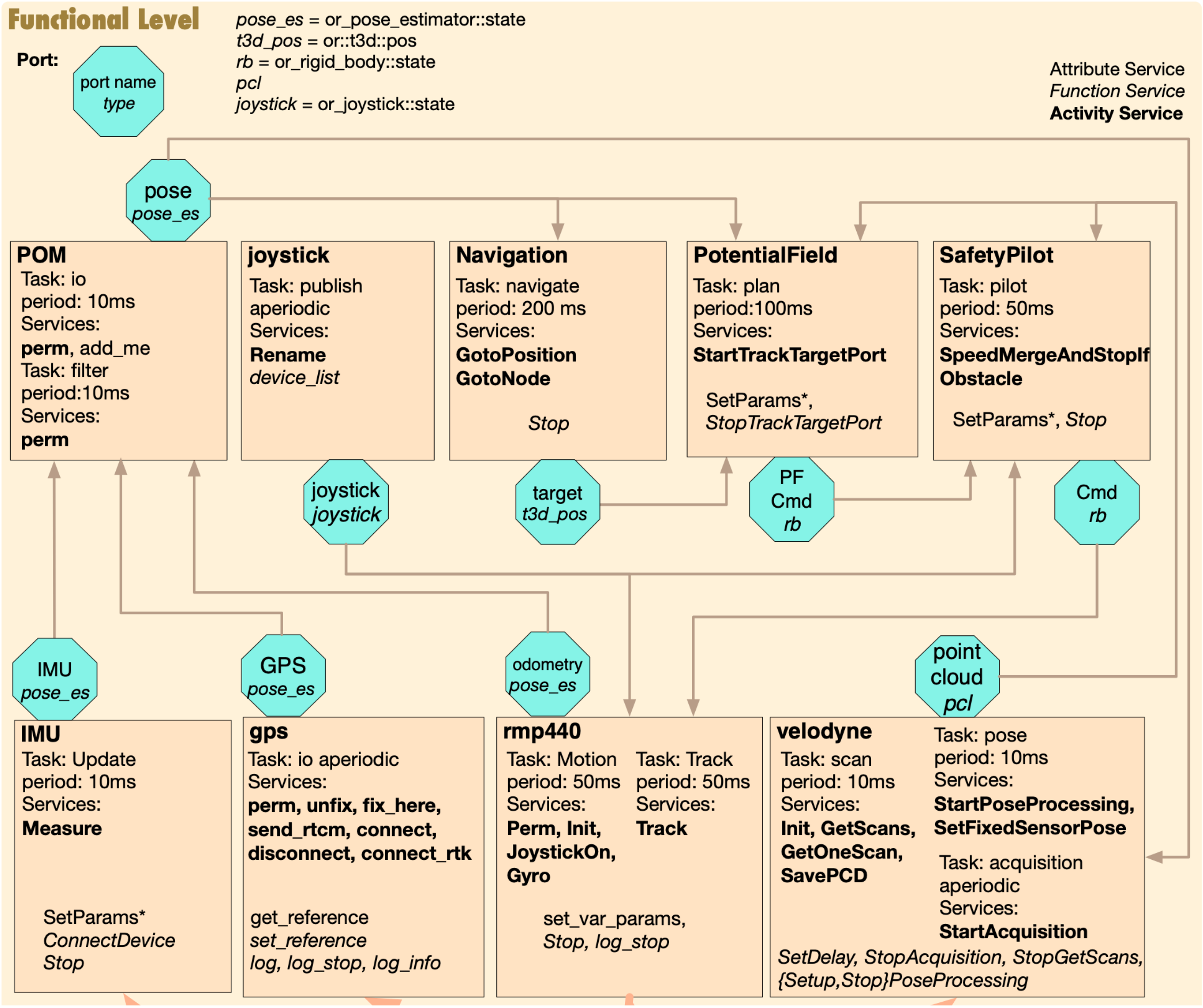
- Motion Capture localization
- IMU (angular velocities and accelerations)
- Control each propeller velocity separately
- Only 1 CPU
- Update frequency is ~ 1kHz



RMP440: Minnie

- Segway RMP 440
- Fast (up to 8 m/s)
- GPS ; Gyro ; IMU ; Velodyne LIDAR
- 2 recent CPUs





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Formal-Model Execution Engine

Experimentations

Generic verification: AnyADL ↔ AnyTool

BPMN

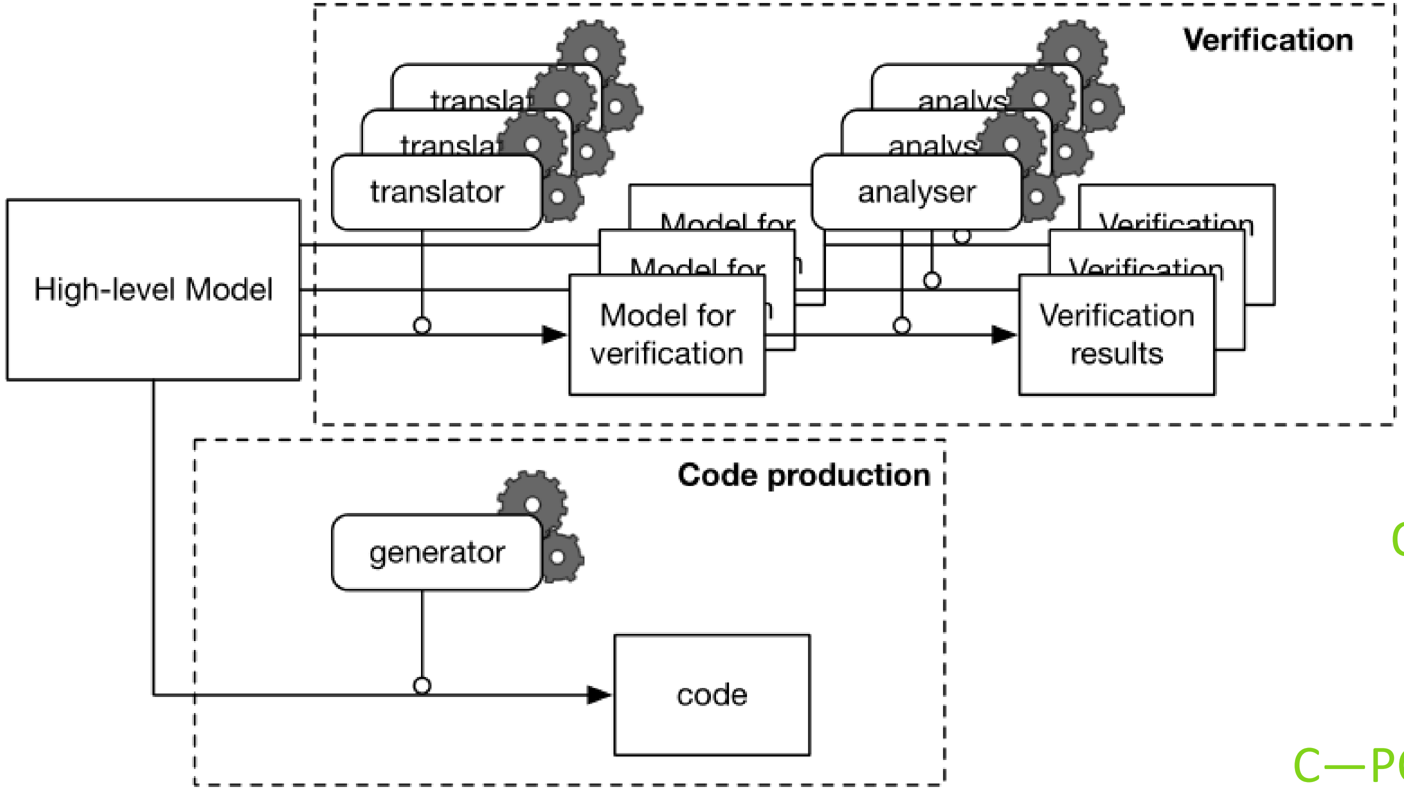
SDL

GenoM

SysML

VHDL

AADL



CADP

SPIN

NuSMV

Tina

Hippo

Uppaal

Ocarina

BIP engine

C—POSIX / Xenomai

Some characteristics of GenoM

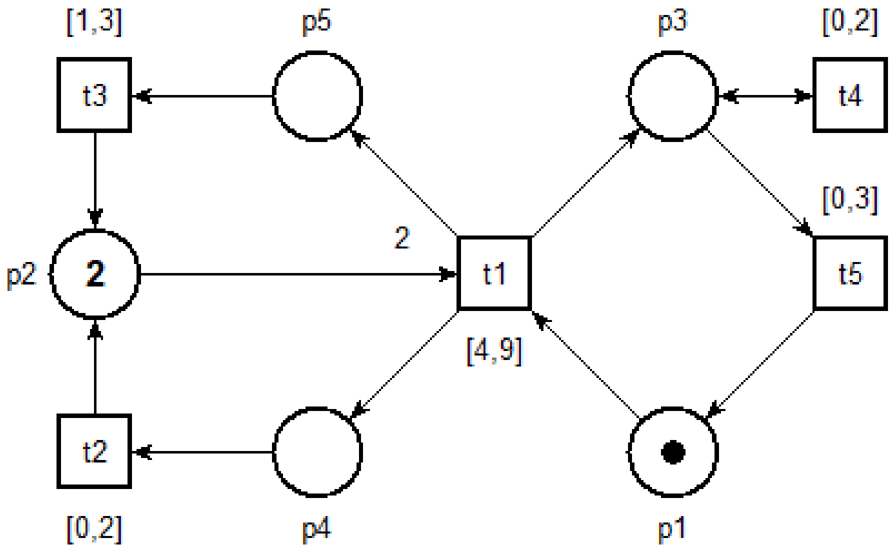
- It is **opinionated**

  Impose a rather “rigid/strict” way to define components, with little room for fooling/messing around. “Everything is here”, as little magic as possible

- It relies on a **templating mechanism** to generate all the artifacts +
- It is explicit about **error handling** and possible **failure scenarios** +
- It is middleware independent
- It uses explicit constructs to express realtime constraints and requirements: tasks; periods; WCET; … +
- Behavioral description based on state machines and synchronization on ports +

Tina

- Modelling based on a Time extension of Petri nets (TPN), with priorities, …
- Historically: checking protocols ; hardware (now SoC) ; architecture exploration ; etc.
- Toolbox with multiple abstraction and verification methods
  - Reachability analysis
  - Simulation
  - Model-checking using different temporal logics




```
Selt version 3.6.0 -- 07/07/20 -- LAAS/CNRS
ktz loaded, 12 states, 29 transitions
0.000s

- [] (t1 => <> t5);
FALSE
  state 0: p1 p2*2
  -t1 ... (preserving - t5 /\ t1)->
  state 12: p3 p4 p5
  -t4 ... (preserving - t5)->
* [accepting] state 15: p2*2 p3
  -t4 ... (preserving - t5)->
  state 15: p2*2 p3
0.000s
```

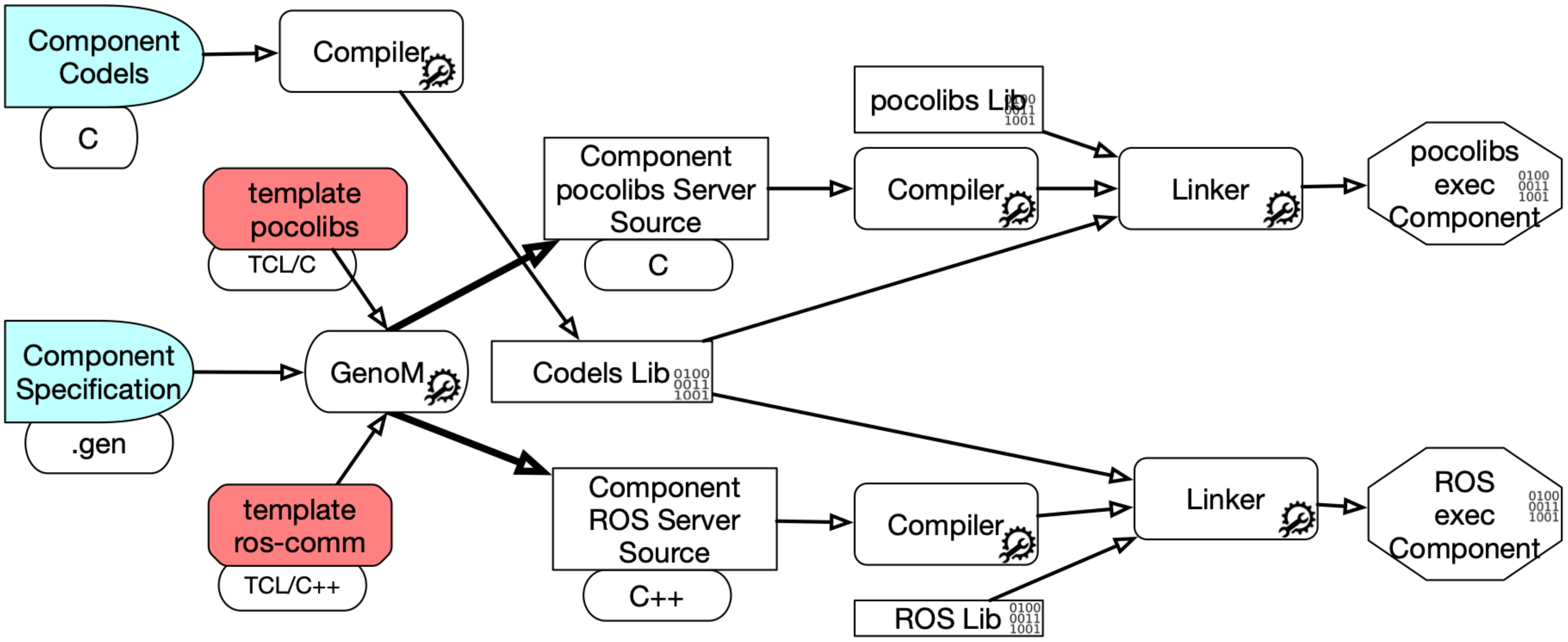
Fiacre and H(ippo)-Fiacre

Think of Fiacre as TPN with datatypes (arrays, structs, fifo queues, …) and components ⇒ it generates TTS

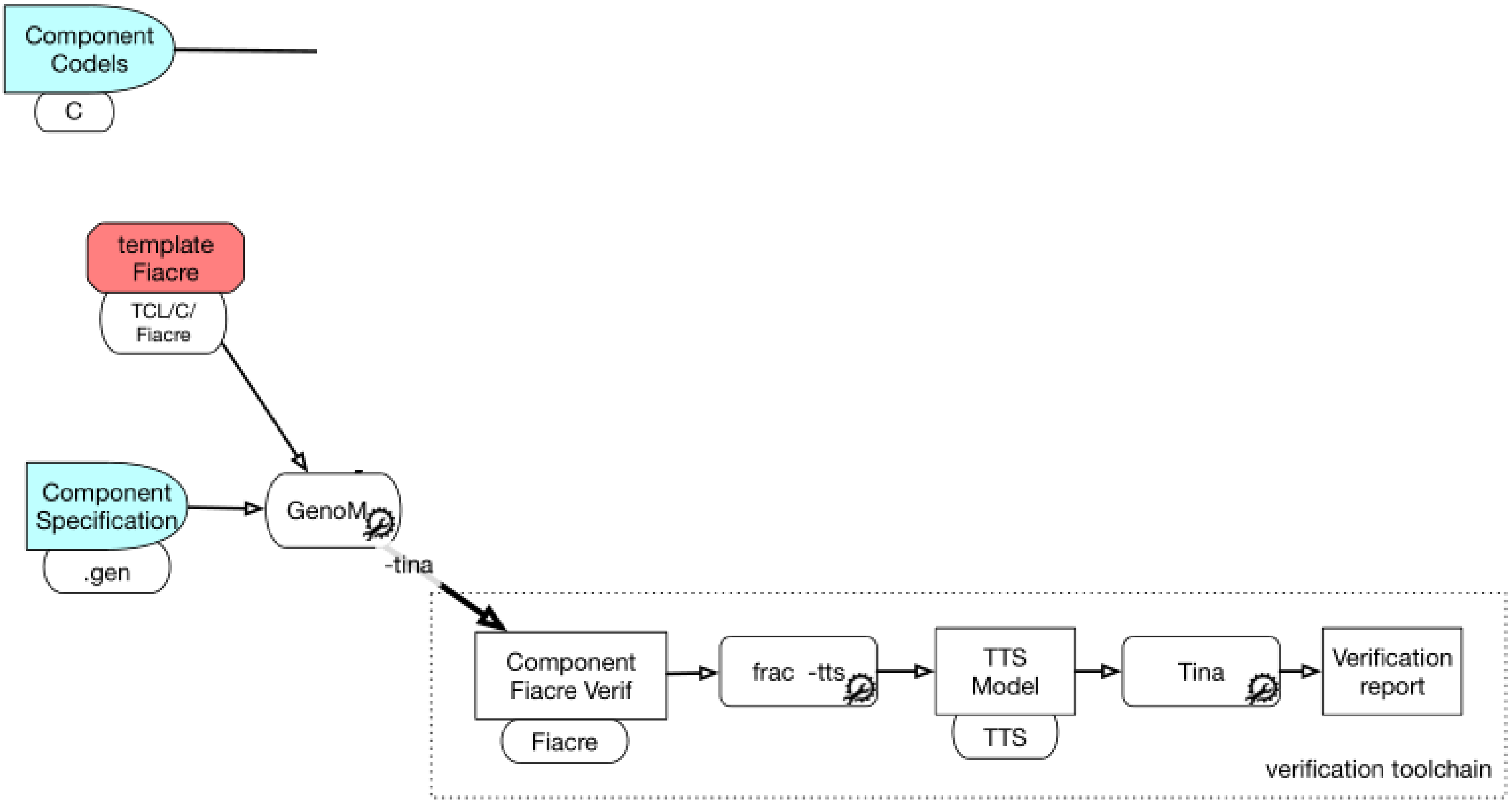
Hippo adds operators for “runtime” tasks and events ⇒ generates executable code

```
type tyEvt is record time : int, id : nat end
type tyDblEvt is array 2 of tyEvt

event e : tyEvt is c_click
task t (tyDblEvt) : nat is c_print

process double_event is
  states wait_first, wait_second, start_print, wait_print
  var tmp : tyDblEvt := [{time=0,id=0}, {time=0,id=0}], ret : nat := 0
  from wait_first
    e?tmp[0]; /* wait first event, assign value to tmp[0] */
    to wait_second
  from wait_second
    select
      wait [200,200];
      to wait_first
    []e?tmp[1];  /* wait second event, assign value to tmp[1] */
      to start_print
    end
  from start_print
    start t (tmp); /* start task t */
    to wait_print
  from wait_print
    sync t ret; /* wait end of task t */
    tmp := [{time=0,id=0}, {time=0,id=0}];
    to wait_first
```

GenoM → executable toolchain

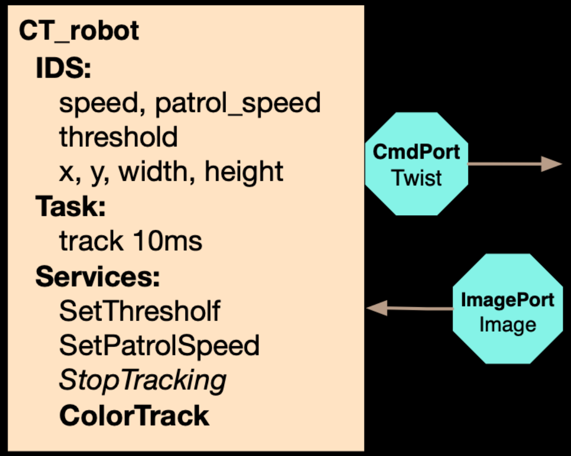


GenoM → Fiacre (verif) toolchain



Short Demo

```
dalzilio@alf MINGW64 ~/Documents/Now/20210709_SHARCV_GENOM/CT_robot
$ sift -M cc.tts cc.ktz
132842 classe(s), 132842 marking(s), 192 domain(s)
4.000s

dalzilio@alf MINGW64 ~/Documents/Now/20210709_SHARCV_GENOM/CT_robot
$ selt cc.ktz -f '[] - dead'
Selt version 3.6.0 -- 07/07/20 -- LAAS/CNRS
ktz loaded, 132842 states, 420232 transitions
0.969s
TRUE
0.000s

dalzilio@alf MINGW64 ~/Documents/Now/20210709_SHARCV_GENOM/CT_robot
$
```



Why mix Robotics and Formal Methods

- Formal verification is one approach, among others, to increase the trust we have in robotic systems
- Already used in many critical domains

  with safety standards: transport, energy, … and without: space, military, …
- It does not solve “all the problems”

  but it is a step in the right direction, and it is very good at challenging preconceived ideas
- It can be integrated in existing frameworks

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Hippo: a Faithfull Execution Engine for H-Fiacre

- The interpretation of GenoM into Fiacre is quite precise; it only lacks knowledge about the behavior of codels
  - We get the state of each execution task and activities
  - We know what messages are exchanged/stored in the IDS
  - We track every timing constraints (timeouts, periods, activations, …)

⇒ We can execute a GenoM specification using a Hippo engine

⇒ This engine if (time-) faithful and predictable

Generic verification: AnyADL ↔ AnyTool

BPMN

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GenoM

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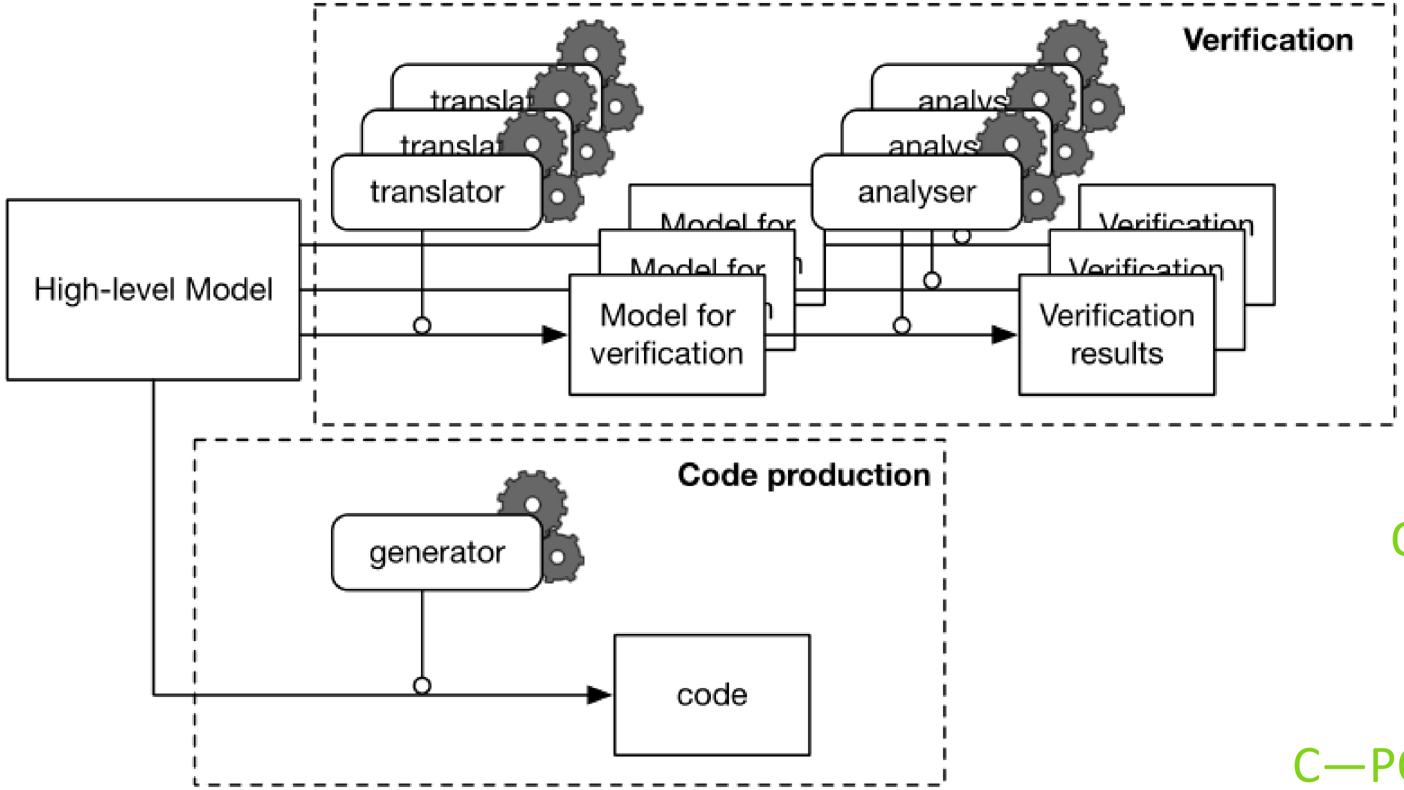

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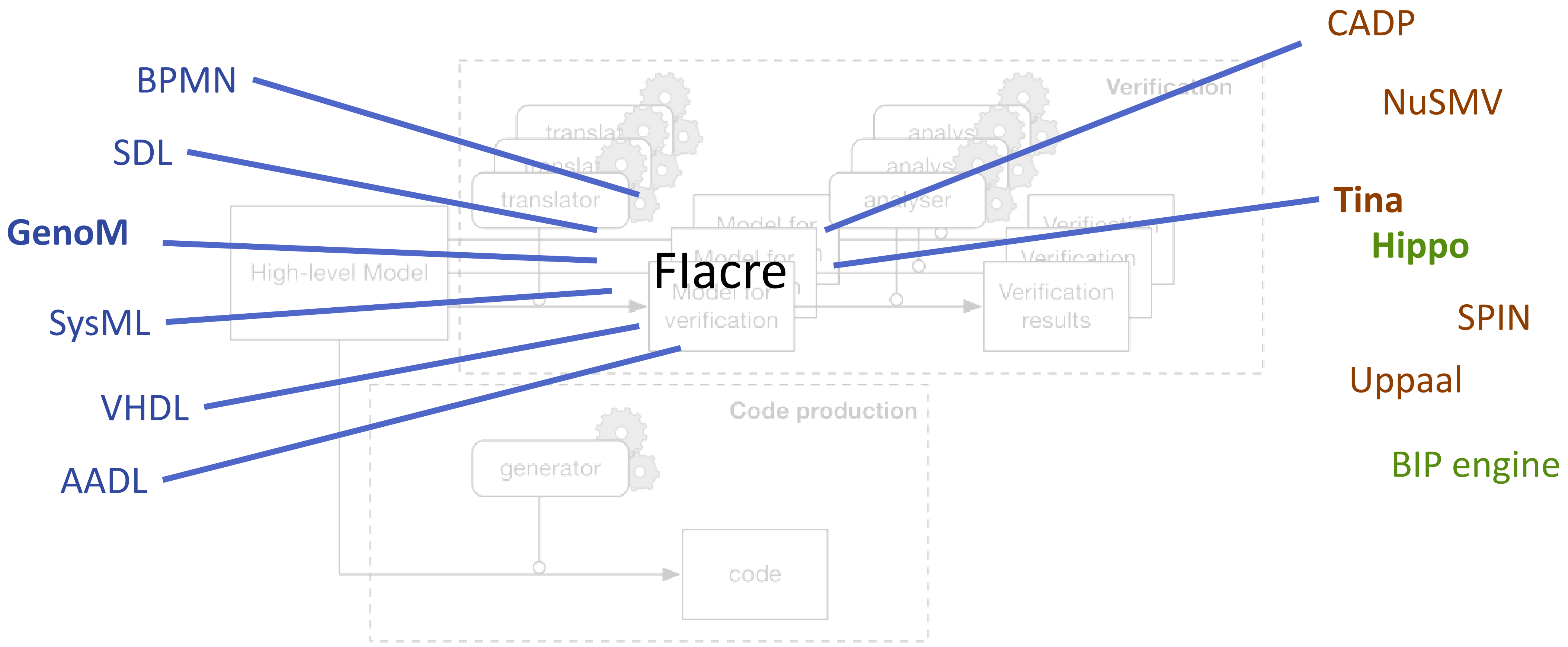
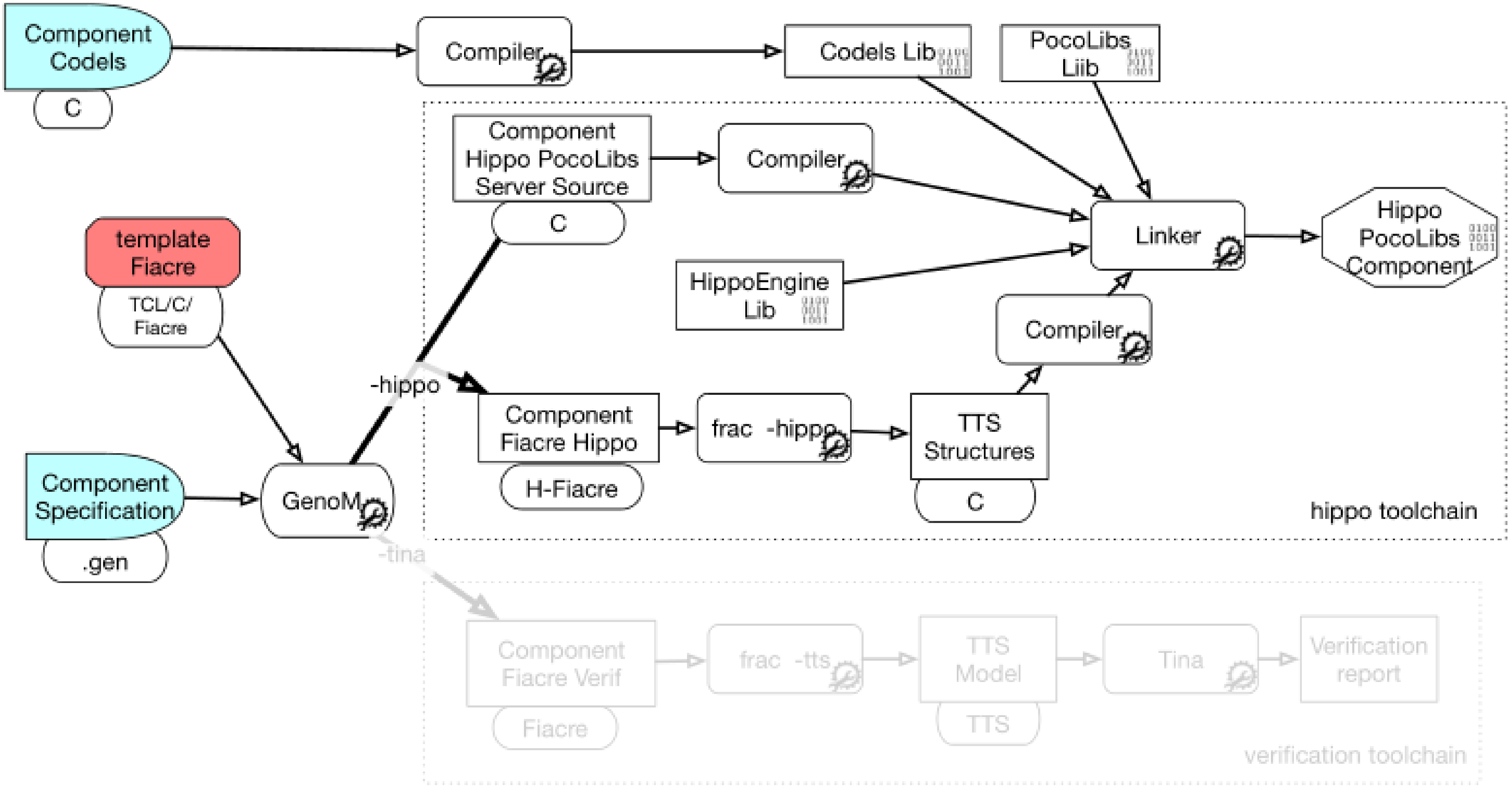


GenoM → Hippo toolchain



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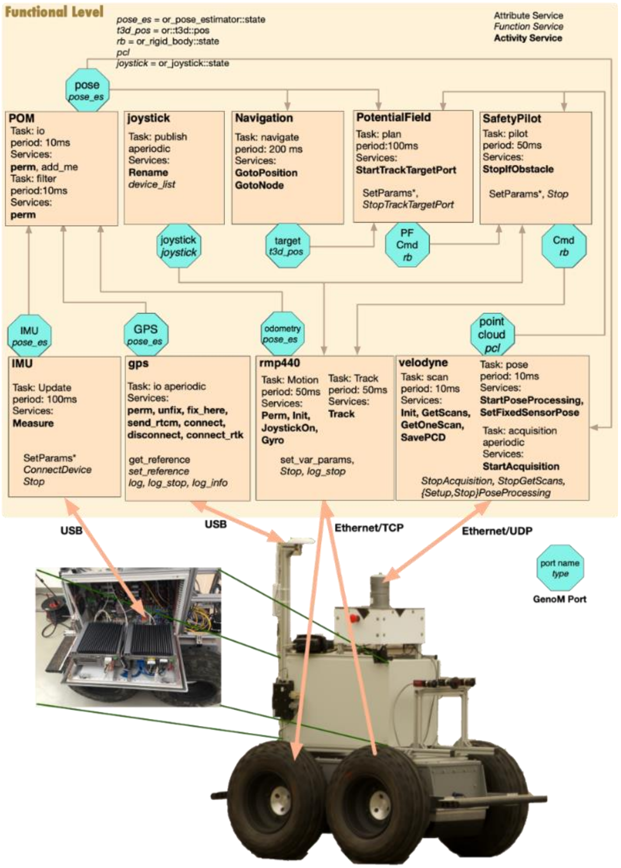
What did we do with all this ?

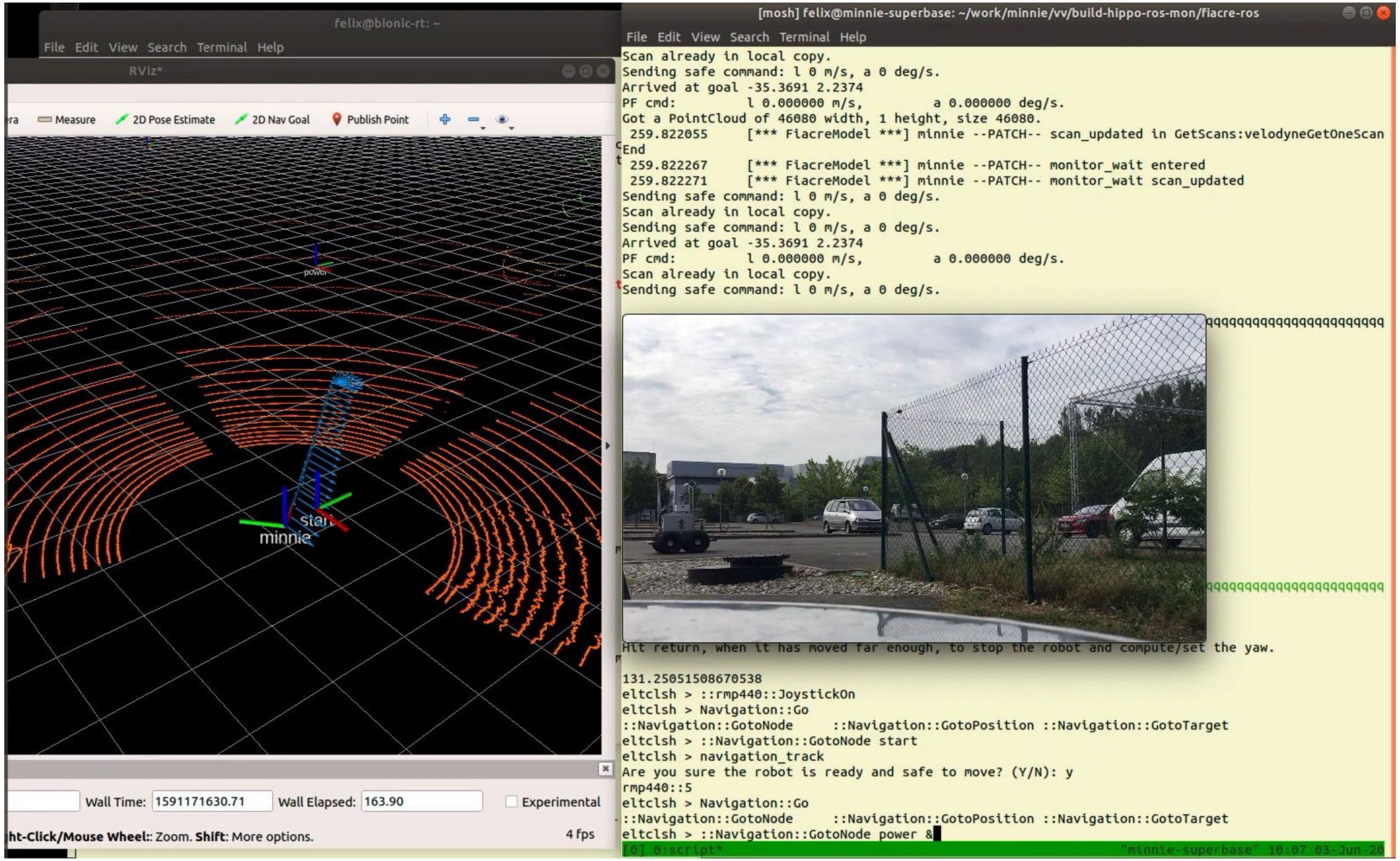
- We used it to check and “run” GenoM specifications (does it run ?)
- We checked properties, “offline” (is it true that … ?)
- A validation of the Hippo Engine (can we trust it ?)

  We check that *runtime executions* $\subseteq$ *traces in the formal model*
- An empirical analysis of the Hippo Engine (does it scale well ?)
- We checked properties, online (can we monitor it ?)

Minnie

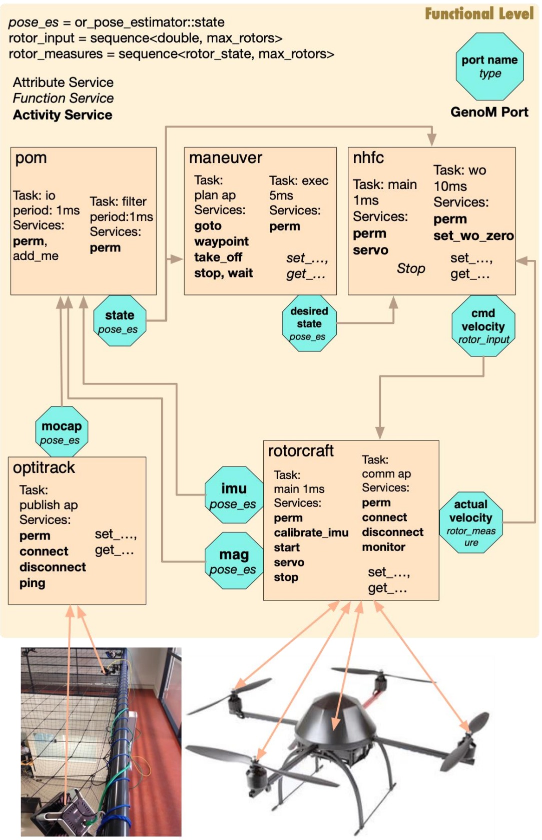
https://youtu.be/vXZiW5tOG54

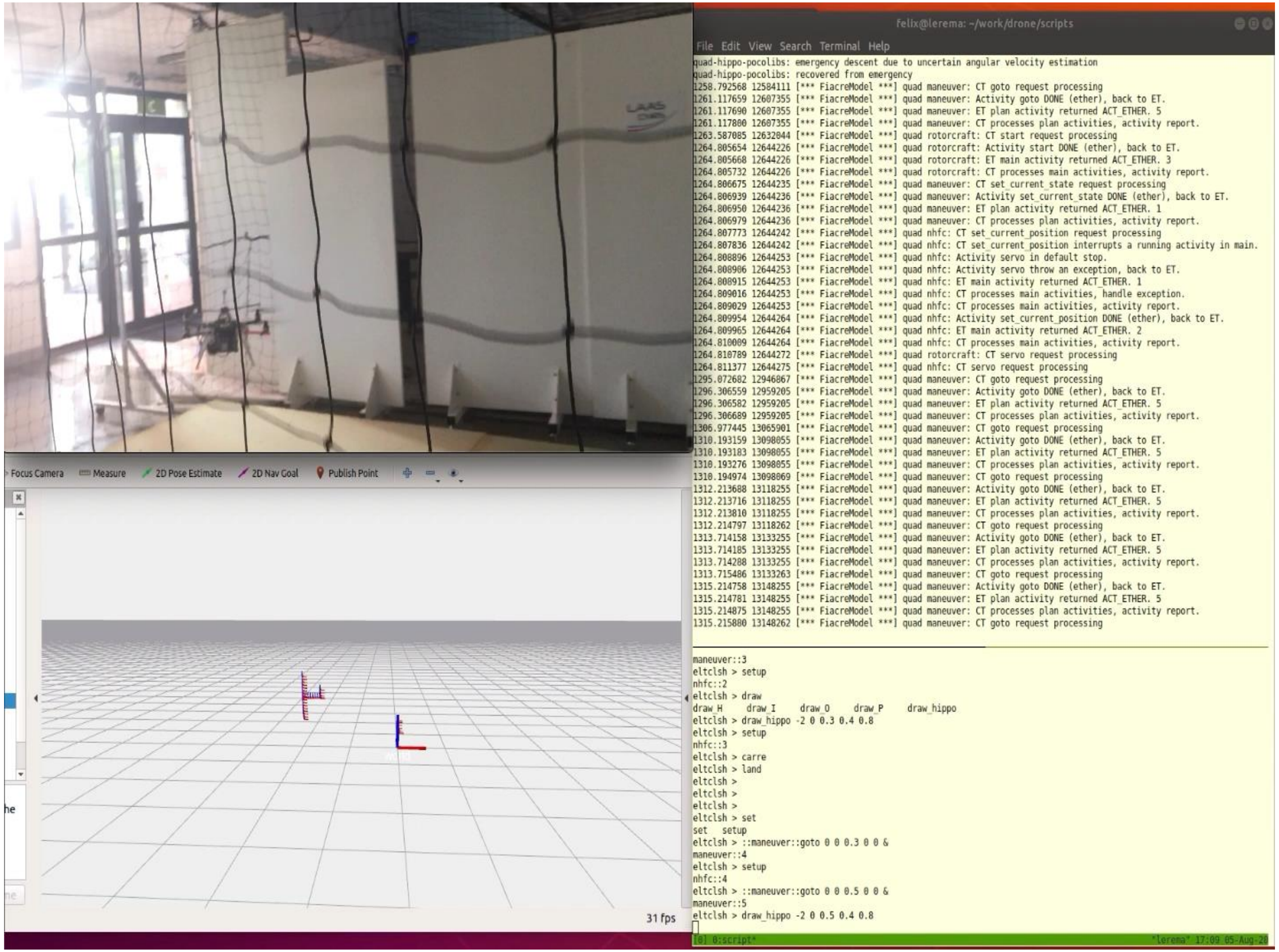




Drone

https://youtu.be/3Ok_c-ATY8I





Controlling Minnie with Hippo

- The GenoM spec for Minnie compiles into a Hippo model with 197 tasks, 9 event ports, 441 extern functions, 1780 (Petri) transitions
- Hippo runs the whole experiment at 10 kHz in one process.
- The load is ≈ 5-10% above normal GenoM usage, without noticeable slowdown
  - We report task period overshoots
  - We detect possibly uninitialized port reads
- The runtime is implemented on Linux (better with PREEMPT_RT) and uses POSIX services with SCHED_FIFO (∼ fixed priority sched.)

Offline Verification for Minnie

- Schedulabity: it is an invariant, `[] - task_overshoot`

  We can take into account the number of cores (we found scheduling errors when using the Velodyne component with less than 3 cores)

- Mutual Exclusion: (also a safety property)

Scenario	*JoystickOn* then *Track*	*Track* then *JoystickOn*
Time	16 min	10 h
#classes	42,714,945	832,778,752
#markings	5,817,082	44,533,432

- Delay to Stop: example of quantitative property

  We found a WCRT of 141 ms (85 cm before we brake),

  To be compared with a WCET of 43 ms for the slowest codel

Conclusion

GenoM3 — https://git.openrobots.org/projects/genom3

Template GenoM3 Fiacre (ROS et pocolibs) — https://redmine.laas.fr/projects/genom3-fiacre-template/gollum/index

Expérimentation sur Minnie RMP440 — https://redmine.laas.fr/projects/minnie/gollum/fiacre

Expérimentation sur un drone — https://redmine.laas.fr/projects/drone-v-v/gollum/index

Papier sur la V&V en robotique — hal-02927311

Papier sur Fiacre/Hippo/GenoM3 — hal-03017661

CI_robot.gen

```
/* ------------------ Activity Services Definition ---------------------- */
activity ColorTrack (in color tracked_color, // the color we want to track in the image
                     out long lost) { // we return how many time we lost the target
  doc      "Produce a twist so the robot follow a color in an image";
  local    boolean found; // to help counting found/lost status
  task     track;        // The task in which ColorTrack instance will execute
  validate ValidateColor(local in tracked_color); // validate the values passed as argument

  // Automata syntax
  // codel <state>  c_function({{ids|port|local}? {in|out|inout} arg_k,}*)
  //                   yield {pause::}?<state_i> {, {pause::}?<sta
  // - ids/port/local is optional if arg_k name is not ambiguous,
  // - start, stop and ether are predefined states,
  // - yield pause::state means transition will wait the next task cycle to lea

  codel <start>   InitColorTrack(local out lost, local out found) yield Find;
  codel <Find>    GetImageFindCenter(port in ImagePort, local in tracked_color
                              ids in threshold, local out found, ids o
                              ids out width, ids out height)
                     yield pause::Find, // no new image, wait next cycle o
                           Lost,        // lost the color
                           CompCmd,     // found the color, compute the sp
                           ether;       // in case of error.
  codel <Lost>    ComputeSpeedWhenLost(ids out cmd, ids in patrol_speed,
                               local out found, local out lost)
                     yield PubCmd;
  codel <CompCmd> ComputeSpeed(ids in x, ids in y, ids in width, ids in height,
                     yield PubCmd;
  codel <PubCmd>  PublishSpeed(ids in cmd, port out CmdPort)
                     yield pause::Find, // Loop back at the search in the next
                           ether;       // in case of error.
  codel <stop>    StopRobot(ids out cmd, port out CmdPort) // stop is a pred
                     yield ether; // ColorTrack execution will jump to this
                                   //service is interrupted
  after      SetPatrolSpeed; // we can only call this service after SetPatr
  throw      bad_cmd_port, bad_image_port, // Possible errors in the codels
             opencv_error, bad_color;      // Any will force execution to e
  interrupts ColorTrack; // Only one ColorTrack service running at a time
 };
};
```