A Verified UAV Flight Plan Generator

FormaliSE 2023

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Paparazzi

Paparazzi is an autopilot for micro-drones

- Developed at ENAC since 2003,
- Open-Source under GPL license.

Complete drone control system:

- Control software part,
- Design of some hardware components,
- Support for ground and aerial vehicles,
- Support for simultaneous control of several drones,
- User can define their own mission using **flight plans**.

Flight Plan

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Example:

1. Wait until the GPS connection is set,
2. Take off,
3. Do a circle around a specific GPS position.
4. If battery is less than 20%: Go *home* and *land*.

Presentation of the Generator

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The **generated C file** contains:

- The Flight Plan Header: definition of constants and variables,
- The main function: `void auto_nav(void)`,
- Auxiliary functions:
  `pre_call_block`, `post_call_block` and `forbidden_deroute`.

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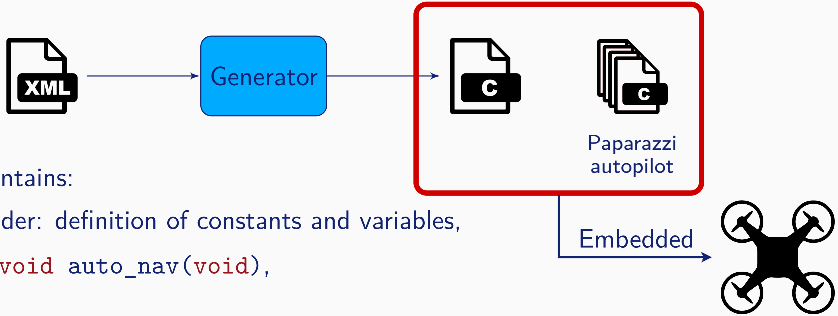

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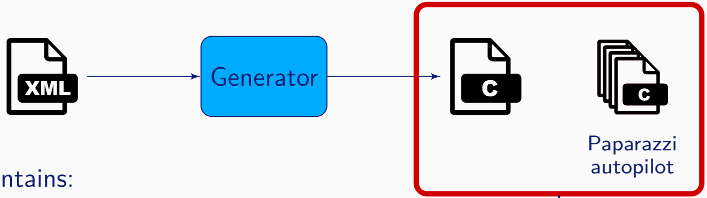

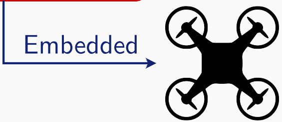

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Function `auto_nav`:

- Called at 20 Hz,
- Sets navigation parameters for actuators.

Motivation

Problems:

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- Does the `auto_nav` function always terminate?
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$\Longrightarrow$ **Certified Compilation problem**

Solutions to similar problems

- CompCert: C compiler proved in Coq.
- Vélus: Lustre compiler proved in Coq.

Coq

Coq is a proof assistant

- Developed by Inria,
- Based on the Gallina language.

Software for writing and verifying formal proofs

- Proofs of mathematical theorems,
- Proofs of properties on programs.

  $\Longrightarrow$ Coq code can be extracted into OCaml code with guarantees.

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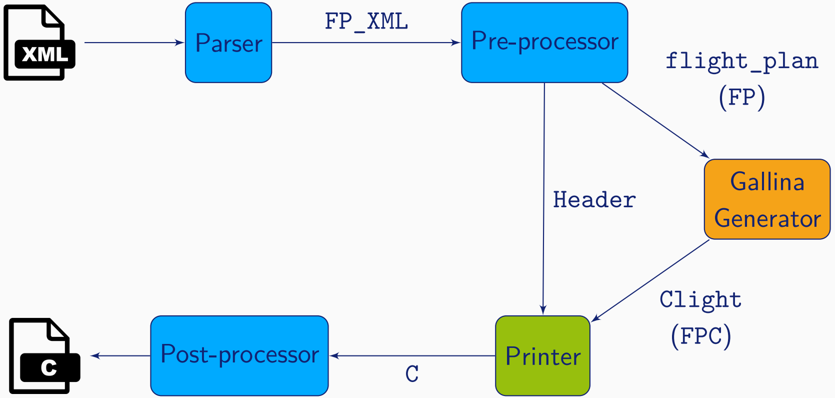
Our solution: New flight plan generator developed and verified in Coq.

New Verified Flight Plan Generator (VFPG)



Pre-processing: Manages included files, converts block names into indexes...
Post-processing: Produces a compilable C code.

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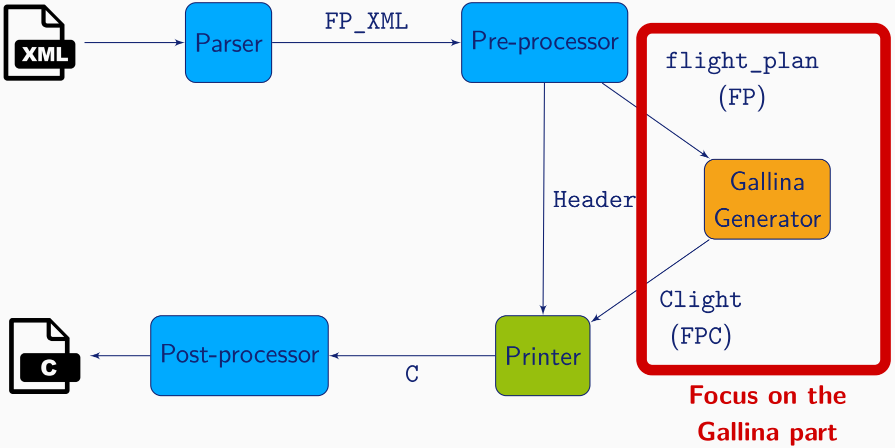

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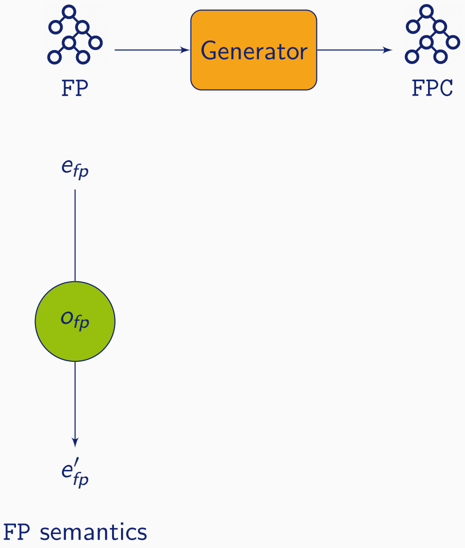

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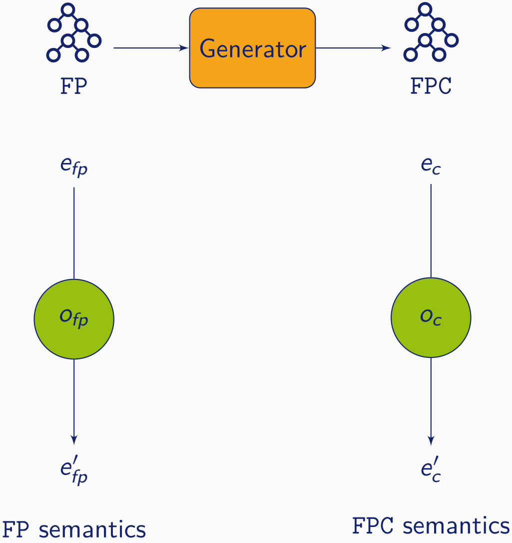

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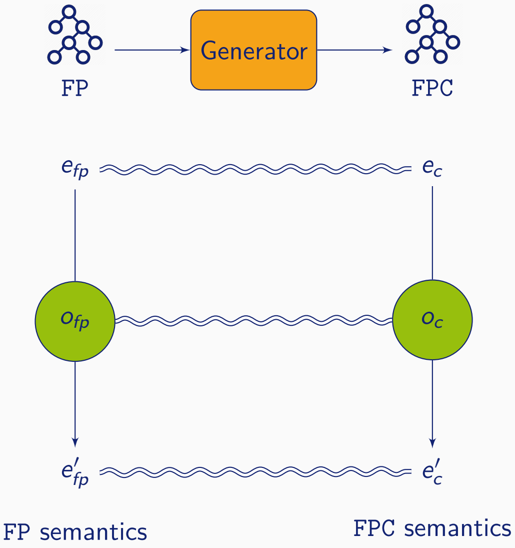

Flight Plan Language

Flight Plan Structure in Gallina

```
Record flight_plan := {
    blocks: list fp_block
    excpts: list fp_exception;
    fb_deroutes: list fp_fb_deroute; (* New feature *)
}
```

```
Record fp_block := {
    id: block_id;
    excpts: list fp_exception;
    stages: list fp_stage;
}.
```

```
Record fp_exception := {
    cond: c_cond;
    id: block_id;
    exec: option c_code;
}.
```

```
Inductive fp_stage :=
  WHILE (cond: c_cond) (body: list fp_stage)
  | SET (var: var_name) (value: c_value)
  | CALL (fun: c_code)
  | DEROUTE (idb: block_id)
  | RETURN (reset: bool)
  | NAV (nav_mode: fp_nav_mode) (init: bool).
```

```
Record fp_fb_deroute := {
    from: block_id;
    to: block_id;
    only_when: option c_cond;
}.
```

Example: Potential Execution of a Flight Plan

Flight Plan:

```
{| excpts : [ ],
   fb_deroutes: [ ],
   blocks : [
    {| id: 0, excpts: [ ],
        stages: [
            CALL "InitSensors()";
            WHILE "!GPSFixValid()" [ ];
            SET "home" "GPSPosHere()"]
    |};
    {| id: 1, excpts: [ ],
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21	10	...
$\vdots$	$\vdots$	$\vdots$

Generator

Generator Function

```
Definition generate_flight_plan:
                     flight_plan → res_generator
```

Inputs:

- Flight plan to convert.

Outputs:

- ```
  Variant res_generator :=
      | CODE (res: Clight.program * list err_msg)
      | ERROR (errs: list err_msg).
  ```
- Warnings and errors currently produced during the generation.
  - detect when there is a possible deroute that is forbidden,
  - detect when the flight plan has an incorrect size.
  ```

Example of generated C Code

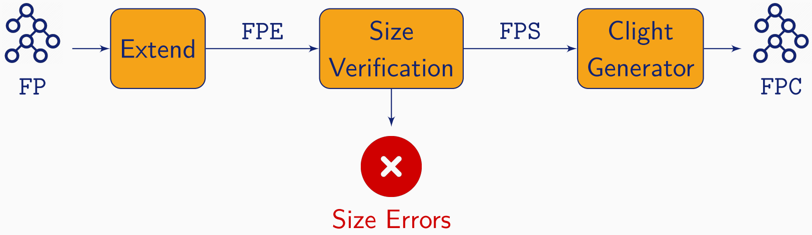
Example of a flight plan:

```
{| excpts: [],
   fb_deroutes: [],
   blocks: [
   {| id: 0,
      excpts: [],
      stages: [
      CALL "func1()";
      CALL "func2()"
      ]
   |}
   ]
|}
```

C code generated:

```
static inline void auto_nav(void) {
    switch (get_nav_block()) {
        case 0: // Block 0
            switch (get_nav_stage()) {
                case 0: // Stage 0
                    func1();
                case 1: // Stage 1
                    func2();
                default:
                case 3: // Default Stage
                    NextBlock();
                    break;
            }
            break;
        case 1: // Default Block
            GEN_DEFAULT_C_CODE()
    }
}
```

Steps of `generate_flight_plan` function



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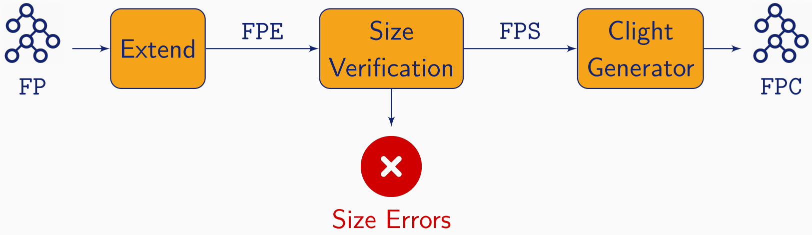

Extended Flight Plan:

- Index stages,
- Split `NAV` into `NAV_INIT` and `NAV`,
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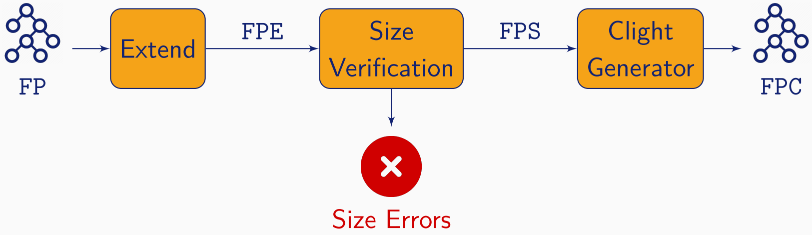

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Size verification:

- Check block indexing,
- Check that numbers of blocks and stages are less than 256,
- Check that `block_id` fields are 8 bits values.

Verification of the Generator

Generic Big Step Semantics for Flight Plans

Definition (`fp_semantics`)

A generic definition for the flight plan semantics.

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```
Record fp_semantics: Type := FP_Semantics_gen {
    (** Environment for the semantics *)
    env: Type;
    (**  Properties stating if an env is an initial environment *)
    initial_env: env → Prop;
    (** Properties stating the execution of the auto_nav function *)
    step: env → env → Prop;
  }.
```

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```

Instanciation of the semantics:

- FP semantics: semantics_fp,
- FPC semantics: semantics_fpc,
- FPE semantics: semantics_fpe,
- FPS semantics: semantics_fps.

FP Semantics: Drone Environment

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From the point of view of the flight plan execution, the global drone environment can be split into 2 distinct elements:

- the memory storing the execution **state** of the flight plan,
- the memory that can be modified by flight plan **external functions**.

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$\Longrightarrow$ **It is not possible to represent the effect of their execution.**

$\Longrightarrow$ **We assume that these 2 memory regions are strictly disjoint.**

FP Semantics: Abstraction of the Drone Environment

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fp_state represents an abstraction of the current state of the flight plan.

```
Record fp_state := {
    idb:  block_id;  stages:  list fp_stages;  (* Current position *)
    lidb: block_id;  lstages: list fp_stages; (* Last position *)
}
```

A **position** is a couple of a block ID and the remaining stages to execute.

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A **position** is a couple of a block ID and the remaining stages to execute.

fp_trace represents the history of external functions execution.

```
Variant fp_event := COND (cond * bool) | C_CODE (c: c_code).
Definition fp_trace := list fp_event.
```

Bisimulation relation

fp_simulation describes if `FP2` can simulate every behaviour of `FP1`.

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```
Record fp_simulation (FP1 FP2: fp_semantics)
                     (match_envs: env FP1 → env FP2 → Prop): Prop := {
  match_initial_envs:
      ∀ (e1: FP1.env), initial_env e1 →
          ∃ (e2: FP2.env), initial_env e2 ∧ match_envs e1 e2;
  match_step:
      ∀ (e1 e1': FP1.env), step e1 e1' →
      ∀ (e2: FP2.env), match_envs e1 e2 →
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}.
```

Definition of a bisimulation relation between 2 semantics.

```
Inductive bisimulation (FP1 FP2: fp_semantics) : Prop :=
  Bisimulation (match_envs: env L1 → env L2 → Prop)
               (forward_simulation: fp_simulation FP1 FP2 match_envs).
               (backward_simulation: fp_simulation FP2 FP1 match_envs).
```

Correctness theorem of the generator

Theorem (bisim_fp_fpc)

$\forall$ `fp prog warnings`,
`generator fp` $=$ `CODE` (`prog`, `warnings`)
$\rightarrow$ `bisimulation` (`semantics_fp fp`) (`semantics_fpc prog`).

This theorem states that the generator preserves the semantics.

Correctness theorem of the generator

Theorem (bisim_fp_fpc)

```
∀ fp prog warnings,
  generator fp = CODE (prog, warnings)
  → bisimulation (semantics_fp fp) (semantics_fpc prog).
```

This theorem states that the generator preserves the semantics.

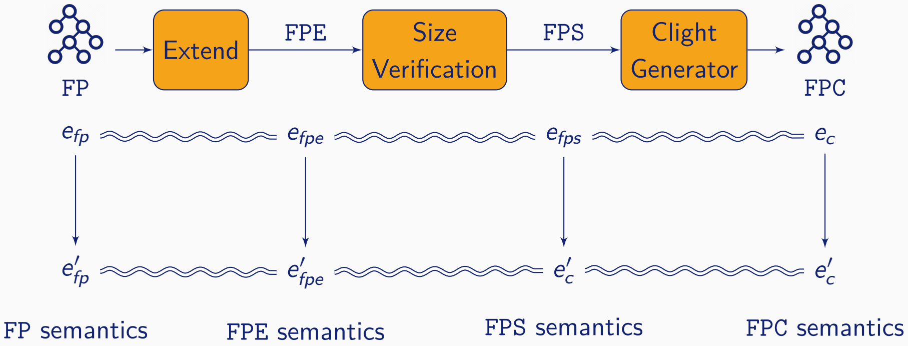
Forward simulation

FP behaviours is simulated by the Clight code.

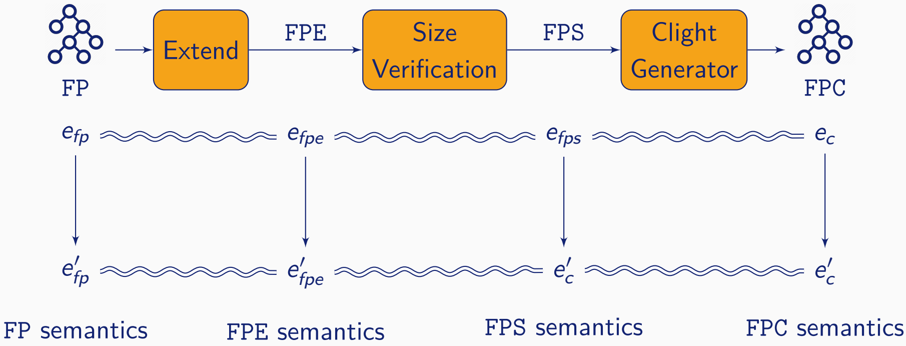
Backward simulation

Every possible execution of the Clight code is described by the FP semantics.

Verification of the `bisim_fp_fpc`



Verification of the `bisim_fp_fpc`




```
Lemma compose_bisimulations:
    ∀ FP1 FP2 FP3, bisimulation FP1 FP2
                  → bisimulation FP2 FP3
                  → bisimulation FP1 FP3.
```

Proof based on axioms

Interpretation of the **arbitrary C code**.

$\Longrightarrow$ `Parameter eval: fp_env → cond → (bool * fp_env).`

$\Longrightarrow$ New axioms to convert arbitrary C code into traces.

Axiom stating that the function **create_ident** is injective.

Classical Coq standard library:

excluded middle, proof irrelevance and functional extensionality.

An axiom to prove that the Clight semantics is deterministic.

not mandatory, will be removed in future work.

Lessons Learned & Conclusion

Lessons Learned

Development methodology

- Constrained by the previous generator:
  Input language, C code generated...
- Split the proof in 3 independent parts.
- Forced clarification of the semantics:
  - Unexpected behaviour (*ex: RETURN after a DEROUTE*),
  - Bug (*ex: the FP contains more than 256 blocks/stages*).

Technical remarks

- 1.3k loc of OCaml and 17k loc of Coq (12% of working code).
- Verification functions produce dependent type.
  $\Longrightarrow$ Avoid axioms, improves confidence in preprocessing.
- Using Clight has some downside.

Conclusion

Summary:

- Development of a new generator in Coq,
- Formalisation of the flight plan semantics,
- New features added,
- Verification of the preservation of the semantics.

Perspectives:

- Remove axiom to prove that Clight semantics is deterministic,
- Verify properties on the flight plan language,
- Integrate the new generator in Paparazzi toolchain,
- Reduce the number of pre-processing steps,
- Generalize the generator.

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