Building a High-Assurance Unpiloted Air Vehicle

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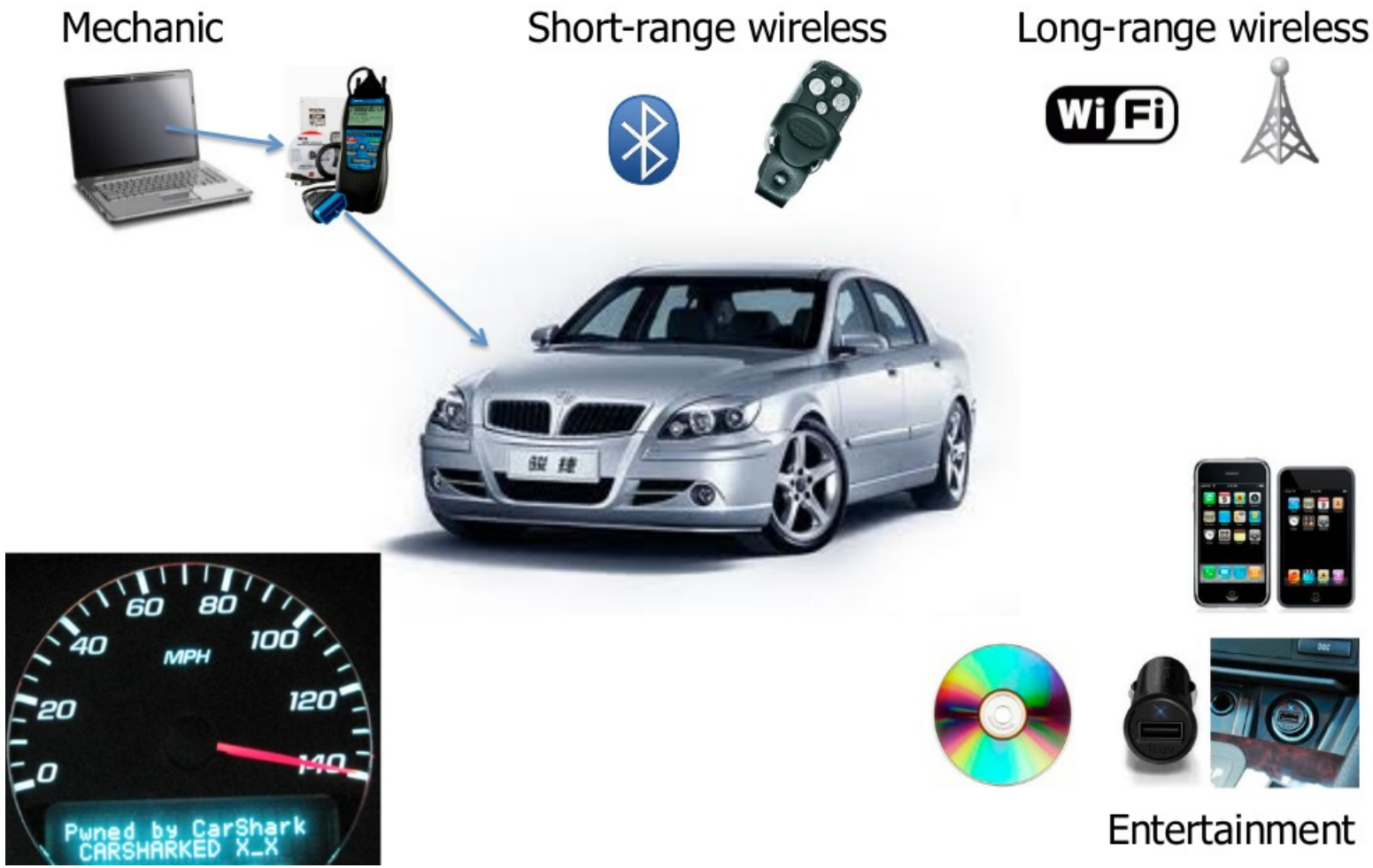
MEMOCODE | Oct 2013

The Problem



src: Kathleen Fisher, http://www.cyber.umd.edu/events/symposium

The Challenge

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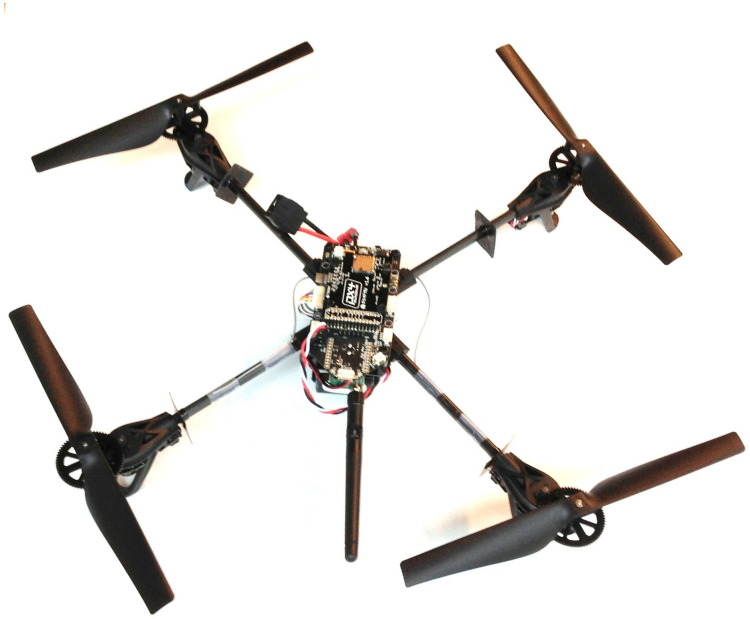
High-Assurance Cyber-Military Systems (HACMS)

PM: Dr. Kathleen Fisher

http://www.darpa.mil/Our_Work/I2O/Programs/High-Assurance_Cyber_Military_Systems_(HACMS).aspx

The “Air Team”



- **Boeing**: military vehicle
- **Galois, Inc.**: autopilot synthesis
- **NICTA**: networking/operating systems

- **Rockwell Collins/Univ. Minn**.: integration and architecture
- **DRAPER/AIS/U. Oxford (Red Team)**: vulnerability analysis

SMACCMPilot

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- Secure
- Mathematically
- Assured
- Composition of
- Control
- Models

This Talk

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How we ~~built~~ have nearly built

- **Ivory**: a memory-safe language/compiler
- **Tower**: an architectural coordination language
- **SMACCMPilot**: a high(er)-assurance autopilot

in 2-3 engineer-years (~1 calendar year).

How We Did It

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1. Collaborate with a vibrant open-source system/community
2. Build **embedded domain-specific languages (EDSLs)** and type-safe macros
3. Synthesize the architecture

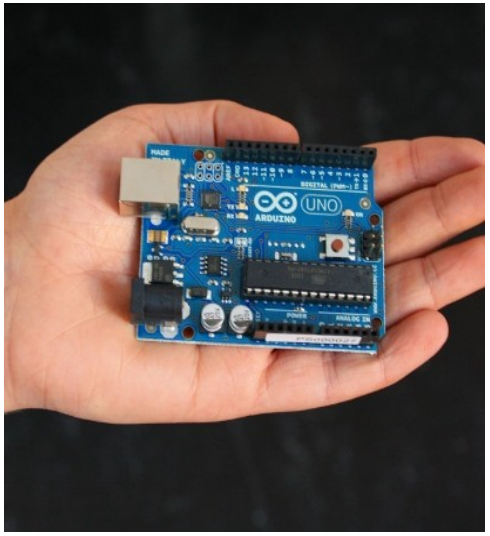
In the Beginning...

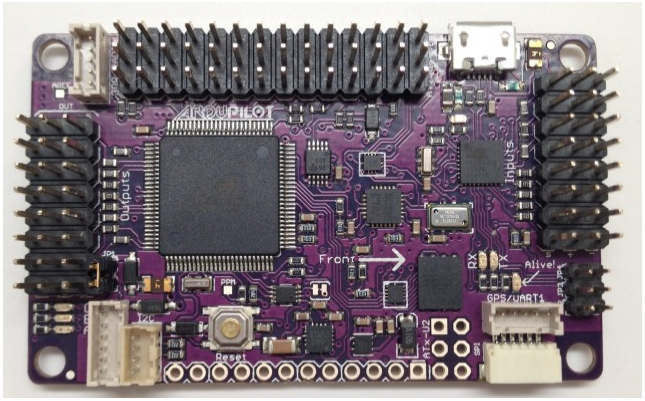
There was Arduino

- Simple 8-bit AVR
- For DIY beginners in embedded systems
- ArduPilot Mega Hardware

  AVR Processor: 8 bit, 16MHz,

  8k RAM, 256k Flash

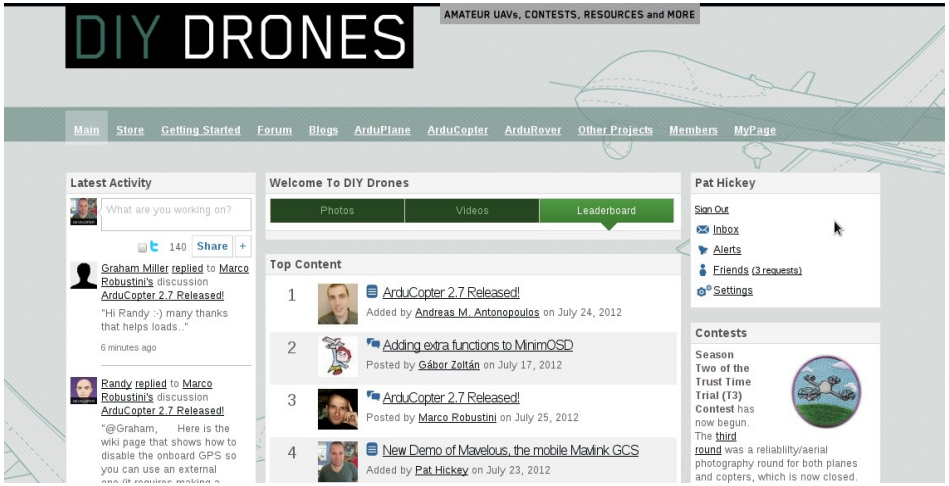




ArduPilot

- ArduPilot
  - Arduino-based
  - Open-source hardware and software
  - 25 volunteer developers worldwide
  - 1000s of users
  - Starting to see commercial use

- DIYDrones.com
  - 30,000 users, 99% amateurs and hobbyists
  - Home of the ArduPilot project
  - Emphasis on beginner friendly



ArduPilot Robustness

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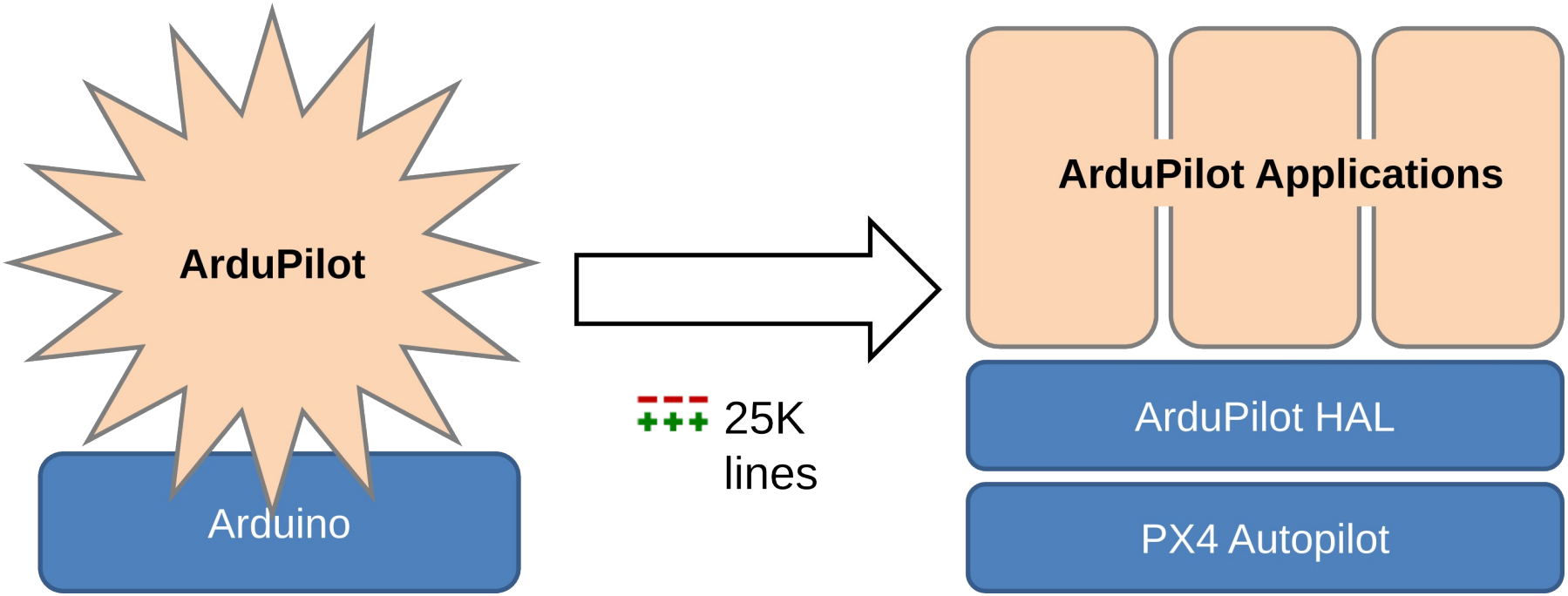
- Monolithic design
- Platform-specific C/C++
- Hobbyist use-cases
  - No communication security, fault-tolerance
  - But being adopted in security-critical environments
- No regimented testing/verification story

The Hardware Abstraction Layer (HAL)



Gave back to the open-source community.
The foundation for ArduPilot now.

Designing a Language for Safety and Security

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Design goal: give the programmer a few centimeters less rope than required to hang herself

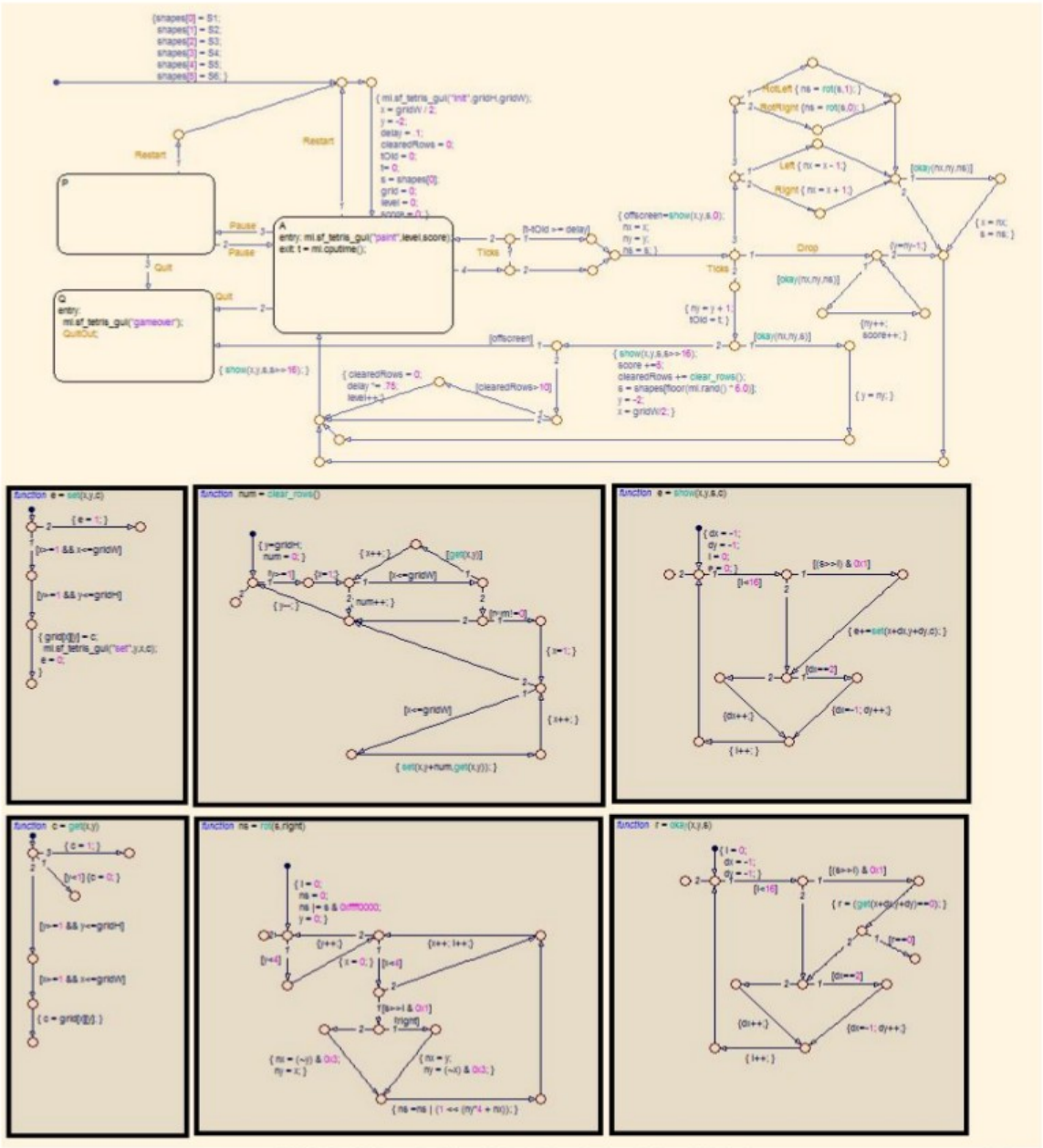
- Help ensure
  - Memory safety
  - Timing safety (i.e., easier WCET analysis)
  - Functional correctness
- While being flexible:
  - bit-data manipulation
  - memory-area manipulation
  - “escaping” to/interrop with C
  - readable generated code

Just…No.

Stateflow model of Tetris game (included in the Stateflow Demo models from the Mathworks!).

Diagram is essentially a control-flow graph of a program that implements tetris.

Much harder to read and modify than an equivalent program.



Model © The Mathworks, 2007

Haskell

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- Strong, static, polymorphic type checking and inference
- Pure, higher-order language—no side effects
- Functional programing for modularity: program composition is function composition

Why Functional Programming Matters by John Hughes (1990)

What if...

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Can we have the high-level abstractions and type-safety of functional programming in embedded systems programming?

Approaches:

- Design a new FP-inspired language/compiler from scratch? **No**:
  - Would take too long
  - No library support
- Take the Haskell compiler and pair it down? **No**:
  - The runtime system is 50KLOCs of C/C--
  - And there's little control over memory usage (it's lazy) and it's a hog--”hello world” takes over 1MB

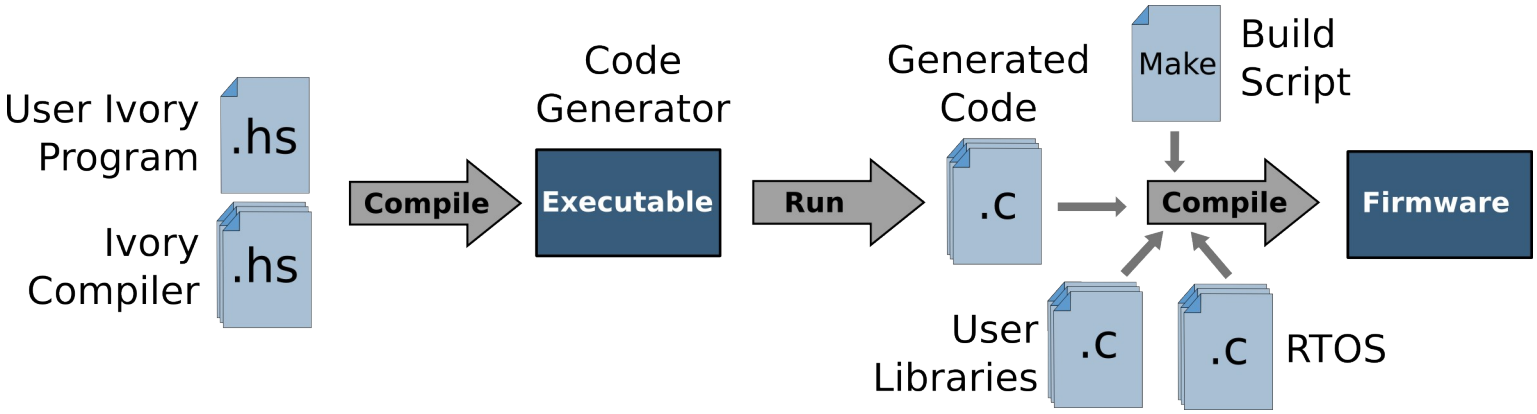
EDSL

Ivory language: 2.5KLOCs
Ivory compiler: 1.2KLOCs

- Building a programming language is hard!
- Get your programming language features for free:
  - Syntax & Parser
  - Type Checker
  - Macro language is type-safe and Turing-complete

"Just" a powerful Haskell library

Compiling and Running Ivory



Who's Used EDSLs?

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- Eaton: garbage truck controllers
- Boeing: component configuration
- Ericsson: DSP
- Xilinx: FPGA synthesis
- Soostone: high-speed trading
- ...

Ivory Example

Loop over an array adding `x` to each element:

```
arrayExample :: Def('[ Ref s (Array 4 (Stored Uint8))
                     , Uint8
                     ] :-> ())
arrayExample = proc "arrayExample"
  $ \arr x -> body
  $ arrayMap
  $ \ix -> do
    v <- deref (arr ! ix)
    store (arr ! ix) (v + x)
```

Type automatically inferred

Map over the elements of the array

Guaranteed dereference `arr` at `ix`

Store `v+x` at index `ix`

Haskell as Type-Safe Macro Language

```
arrayExample :: Def('[ Ref s (Array 4 (Stored Uint8))
                     , Uint8] :-> ()
                     )
arrayExample = proc "arrayExample"
  $ \arr x -> body
  $ arrayMap (arrAdd arr x)
  $ \ix -> do
      v <- deref (arr ! ix)
      store (arr ! ix) (v + x)
```

Type-safe Haskell function call:
No overhead in generated code

```
arrAdd :: (Num a, SingI len, IvoryStore a)
    => Ref s (Array len (Stored a))
    -> a
    -> Ix len
    -> Ivory eff ()
arrAdd arr x ix = do
  v <- deref (arr ! ix)
  store (arr ! ix) (v + x)
```

And arbitrary data-types

Can be used for arbitrary-length arrays

Macros, Example 2

```
data Cond eff = Cond IBool (Ivory eff ())

(==>) = Cond

cond [] = return ()

cond (Cond b f : cs) = ifte_ b f (cond cs)
```

```
ifte (x >? 100)
 (store result 10)
 (ifte (x >? 50)
   (store result 5)
   (ifte (x >? 0)
     (store result 1)
     (store result 0)))
```

```
cond
  [ x >? 100 ==> store result 10
  , x >? 50  ==> store result 5
  , x >? 0   ==> store result 1
  , true     ==> store result 0
  ]
```

Ivory Memory-Safety

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- No null pointer dereferences
- No out-of-bounds array-indexing
- No unsafe implicit casting
- No unexpected type coercions—even satisfying the C standard!

Distilled ArduPilot bug discovered by Galois:

```
...
uint8_t a = 10;
uint8_t b = 250;
printf("Answer: %i, %i", a-b > 0, (uint8_t)(a-b) > 0);
...
```

Answer: 0, 1
Assuming `int > uint8_t`

Ivory: What We Removed

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- No heap allocation (only stack)
- Unbounded looping combinators

  Except for a single `forever` combinator
- `void` type
- Machine-dependent sizes (modulo `float`, `double`)
- Side-effecting expressions
- Pointer arithmetic

Ivory: What We Added

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- Effect types
  - **Allocation effects**: “This function can't (stack) allocate memory”
  - **Escape effects**: “No break is allowed in this loop”
  - **Return effects**: “This macro cannot contain a return statement”
- References (guaranteed non-null pointers)
- Array map/fold combinators
- Automatic assertions
  - arithmetic underflow/overflow
  - div-by-zero
  - user-specified assertions

Ivory: TBD

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- Sum types (unions)
- Fat pointers/strings
- Function pointers
- A better module system
- Interpreters for embedded software

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Tower

Tower: a Glue Code Macro Language

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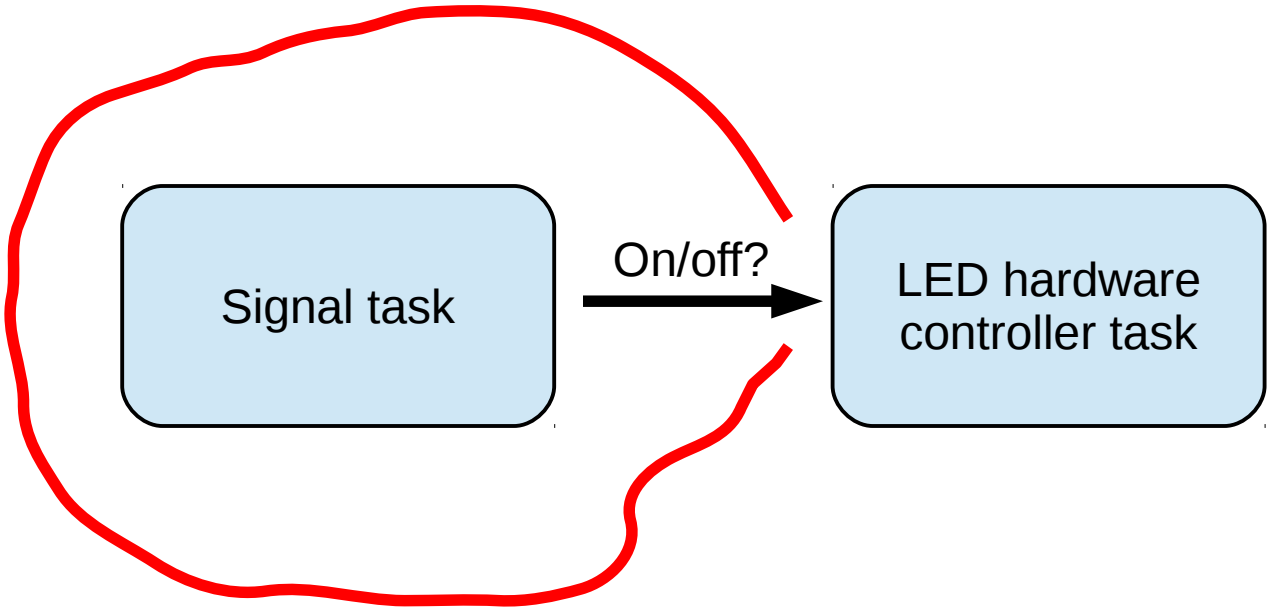
- Goal: address the "glue code" problem: task initialization and communication.
  - Specifies how a tasks are scheduled and communicate

    Pub/sub model
  - Provides both time-triggered and event-triggered behaviors
  - Channels (queues) and data-ports (shared data) communication
  - Able to specify both interrupt handlers and user tasks
- Tower is "just" Ivory macros so has all the type-safety guarantees of Ivory—and no new code generator!

Tower example



Signal Task

Tower

```
blink :: SingI n
      => ChannelSource n (Stored IBool)
      -> Task ()
blink chan = do
  tx <- withChannelEmitter chan "bTx"
  onPeriod period
           (body tx period)

  where period = 100 :: Integer
```

Specify the output channel

Specify when computation takes place

What the task actually does

Ivory

```
body ::(SingI Nat n, GetAlloc eff ~ Scope cs)
     => ChannelEmitter n (Stored IBool)
     -> Integer
     -> a
     -> Ivory eff ()
body tx period currTime = emitV_ tx (even currTime)
  where
  even = currTime .% (2*p) <? p
  p    = fromIntegral period
```

Send 0,1,0,1 ...

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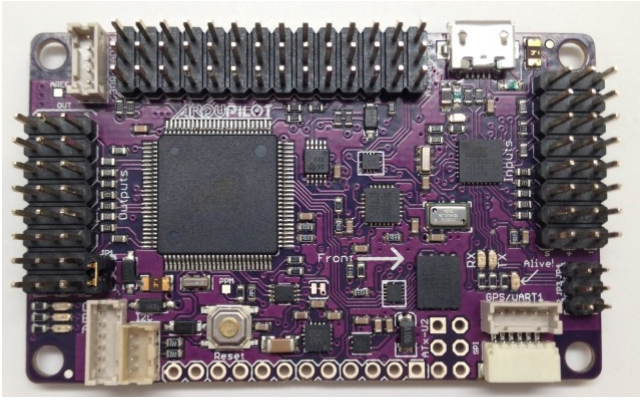
SMACCMPilot

The Hardware

- ArduPilot Mega Hardware (Legacy)

  AVR Processor: 8 bit, 16MHz,

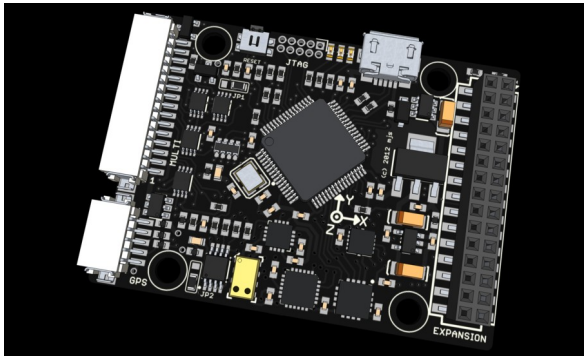
  8k RAM, 256k Flash



- PX4 Hardware (SMACCMPilot)

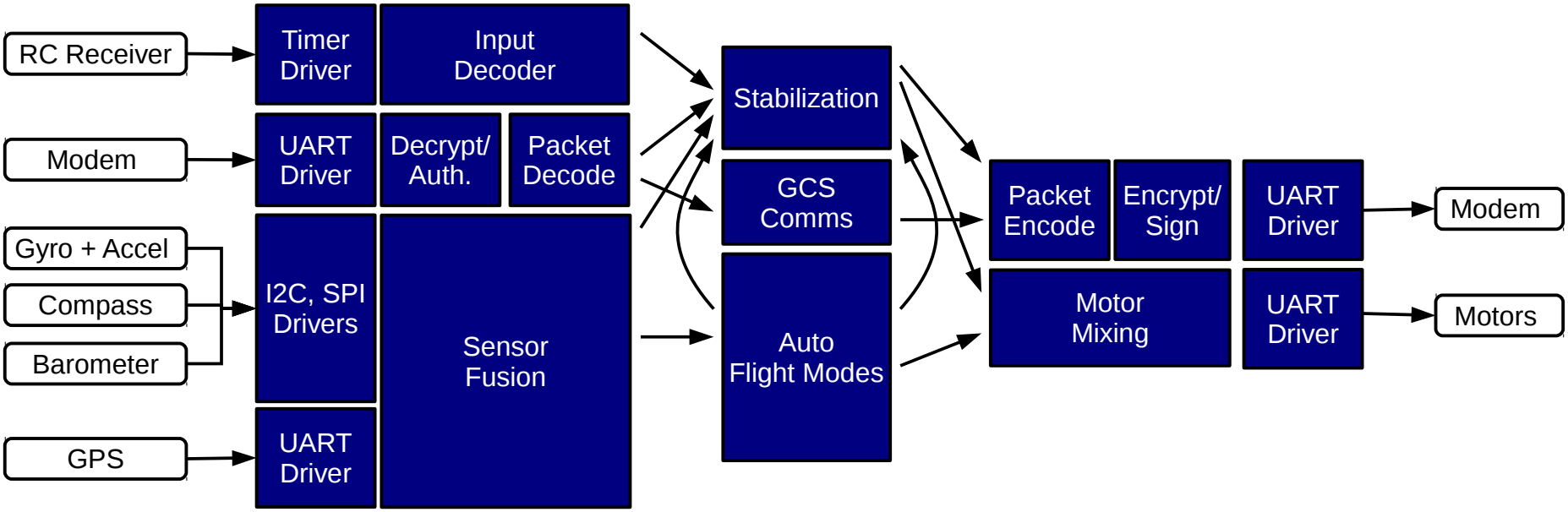
  ARM Cortex M4 Processor: 32 bit,

  168Mhz, 192k RAM, 1024k Flash

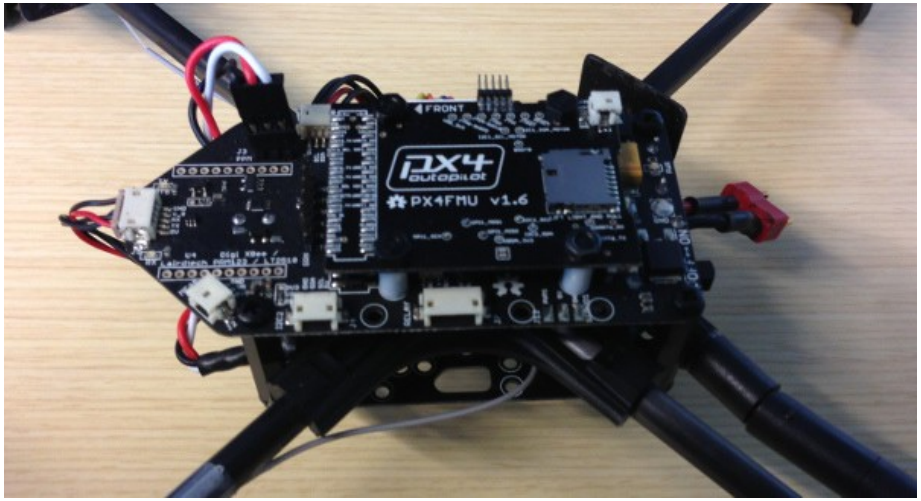


https://pixhawk.ethz.ch/px4/en/start

SMACCMPilot Architecture



Approx. 5x code generation



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SMACCMPilot | Home | Hardware | Software | About

SMACCMPilot

An Embedded Systems Software Research Project

We're building open-source autopilot software for small unmanned aerial vehicles (UAVs) using new high-assurance software methods.

The SMACCMPilot autopilot software:

Hardware Guide

Complete instructions for building a SMACCMPilot based quadcopter.

Get flying »

Software Guide

Learn about how the SMACCMPilot software platform works, and how to develop for it.

Get hacking »

Open Source

The SMACCMPilot platform is an open-source project, released under a liberal BSD license.

Find it on Github »

And the technology used to build it:

Ivory Language

SMACCMPilot is the flagship project of a new programming language called Ivory, a domain specific language for safe systems programming.

Learn about Ivory »

Ivory Tutorial

Walk through an Ivory program with annotations introducing some of the features of the language.

Ivory Tutorial »

Tower Framework

Tower is a framework for composing Ivory programs into multithreaded applications.

Tower Overview »

Lessons Learned/Open Problems

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- Memory safety isn't a pancea
  - We still test/debug/verify
  - Traceability from DSLs to object code is necessary
  - But the kinds of bugs is restricted: seg-faults, memory leaks don't happen
- EDSL shortcomings:
  - Reusing a general-purpose type-checker
  - Requires host-language knowledge
  - Abstractions/macros can affect performance
  - Compilation cycle
- Interpreters for embedded systems are hard
- Have not proved architectural properties or verified controllers

Questions