Software for a Total Artificial Heart

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REALHEART

Background

- Today, heart disease is one of the leading causes of death in the western world
- About 50,000 patients world wide are placed on a heart transplantation list annually
- Shortage of donor hearts is causing many patients to die before transplantation

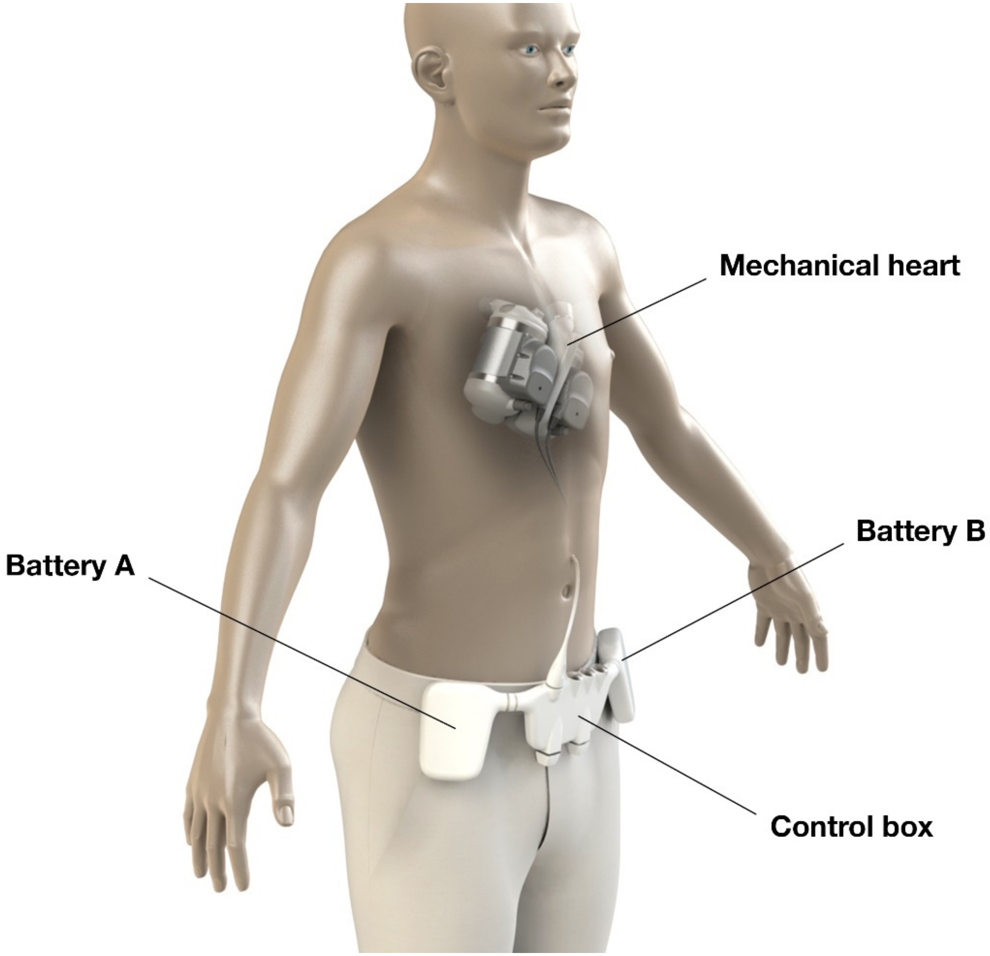
Background

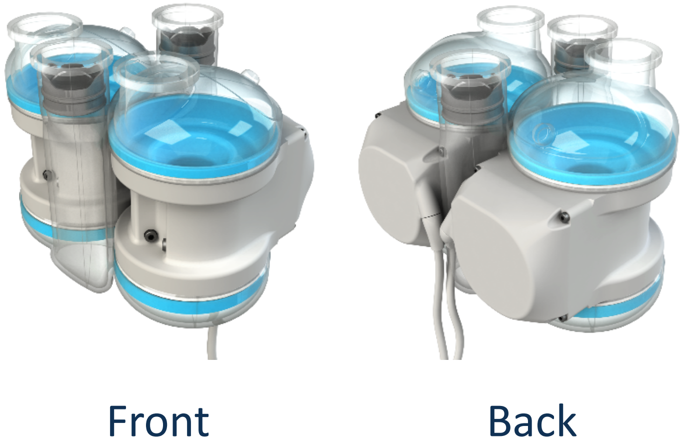
- Scandinavian Real Heart is developing a Total Artificial Heart (TAH)
- A Total Artificial Heart *replaces* the natural heart, unlike Ventricular assist devices (VADs)
- Initially intended for bridge-to-transplant therapy
- Currently in a *preclinical* stage, meaning:
  - Research and development
  - No formal safety requirements for the development process (for cost reasons)
  - No testing in humans, mostly lab testing, but animal testing for verification

Design features

- As realistic as possible
- Pulsating outflow
- Heart rate and stroke volume can be changed within realistic ranges
- Two halves that pump synchronously, each having:
    - a BLDC motor, controlled by
    - a STM32F4 ARM microcontroller
    - two valves (just as the human heart)
    - an atrium and a ventricle (just as the human heart)

Design overview





Blood flow

The need for verification of the software

- You don’t want your heart to crash or hang
- There is no Ctrl + Alt + Del on the heart
- You’d rather not try the typical “turning it off and on again” trick

- You’d rather want it to work all the time…

Software verification via proof

- All software in written in Ada/SPARK
- Some properties have been *proved* statically using GNATprove, for example:
  - Correct data initialization and data flow
  - Correct program flow
  - No array access out-of-bounds
  - No error-prone features such as pointers
  - Settings (e.g. heart rate) guaranteed to be within bounds
- Stack usage verified with GNATstack

Examples of proven properties

- Specific type used for indexing an array type

```
type Phase_Type is (PhaseA, PhaseB, PhaseC);
for Phase_Type use (PhaseA => 0,
                    PhaseB => 1,
                    PhaseC => 2);

type Hall_Sensor_Values is array (Phase_Type) of Boolean;
```

- This allows SPARK to *prove* that every array access will be within bounds
  - This use of types can be done in Ada, it does not require SPARK

Examples of proven properties

```
procedure Update (This        : in out PID_Controller_Type;
                  Error       : Float;
                  Delta_Time  : Time_Sec; -- Seconds since last update
                  Output      : out Float;
                  P_Out       : out Float;
                  I_Out       : out Float;
                  D_Out       : out Float) with
  Global => null,
  Depends => ((This, I_Out, D_Out, Output) => (Error, Delta_Time, This),
              P_Out                        => (Error, This)),
  Pre => (Delta_Time > 0.0);
```

- Verification of program flow:
  - This procedure will not depend on, nor affect, any globals
  - The output parameters **This**, **I_Out**, **D_Out** and **Output** shall depend on **Error**, **Delta_Time** and **This**
  - **P_Out** shall only depend on **Error** and **This**
- These properties will be *proven* by GNATprove

Examples of proven properties

- A type used to define heart rate is given a limited range
  - This use of types can be done in Ada, does not require SPARK

```
Max_Heart_Rate : constant Unsigned_8 := 170;
Min_Heart_Rate : constant Unsigned_8 := 15;

type Heart_Rate_Type is range Min_Heart_Rate .. Max_Heart_Rate;
for Heart_Rate_Type'Size use 8;
```

- Maximum or minimum heart rate is easy to change

Examples of proven properties

- Precondition: The buffer can’t be full before calling the procedure
- Postcondition: The buffer can’t be empty after calling the procedure

```
procedure Put (This     : in out CAN_Buffer;
               Message  : in  CAN_Message_Type) with
  Pre => not Full (This),
  Post => not Empty (This);
```

- Pre and post conditions are *checked* in Ada,
  In SPARK they are *proven* by GNATprove (if possible)

But what if the buffer is full?

- Handle it!
- Or don't!

```
procedure Push_To_Receive_Buffer (Message : CAN_Message_Type) is
   Full : constant Boolean := Receive_Buffer.Full;
begin
   -- Please note that nothing will be done if the Buffer is full,
   -- the mesage will be lost!
   if not Full then
      Receive_Buffer.Put (Message);
   end if;
end Push_To_Receive_Buffer;
```

Pros of software verification via proof

- Lesser need for software testing (properties are proved rather than tested)
- Lesser need for code review
- Errors detected earlier (during compiling or verification)
- Fewer errors later during system testing
- No “once in a blue moon” errors
- Only logical errors
(i.e. it’s really *my fault* if the code doesn’t work… ☹)

Cons of software verification via proof

(Yes, there are some…)

- Risk of over-reliance on proof (not testing enough)
- Remember, no matter how good your tools are, you still need to do a good job!

- It's harder to google your problems (the Ada/SPARK world is small)

- Steep up-front learning curve (you're probably used to C/C++…)
- Initially time consuming to write contracts
- It is really hard to write contracts (other than trivial ones)

Advice for future users

- Learn to use your tools
  - Start with a small test project and play around with it, try all Ada/SPARK features with on it
- Begin with the end in mind
  - Start with a good software architecture from the beginning
  - Add contracts from the beginning
- Ask for help, don’t bang your head against the wall…
- …you can find better use for your head
- …and for the wall

Questions?

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