Part III

Appendices
Semi-formal software specification

As mentioned in Section 5.4.2 on page 50, Drakon [184] notations are used in the present study to build test oracle. Below is the list drakon notations used in the present work:

A.1 List of Drakon notations

Figure A.1: An example of a function "add", returning the sum of its parameters: A and B

Figure A.2: A function call

Figure A.3: Inline and standalone comments
A. Semi-formal software specification

---

Although, very few notations in Drakon are suitable for Erlang; the flexibility in specification is achieved through functional programming constructs of Erlang programming language such as: list comprehension, map, filter, fold, recursions, etc.
A. Semi-formal software specification

(a) Doubled_Array = [ X*2 || X <- Array ]

(b) Greater_Than_Zero_Values = [ X || X <- Array, X > 0 ]

Figure A.6: Map and filter using list comprehension: (a) Map and (b) Filter

A.2 An example of semi-formal specification

The graphical semi-formal specification in Drakon is converted to the Erlang [185] programming language, which acts as an executable specification. Below is an example of FSHS specification:

```erlang
main
End
[ Gate_Open_Args, Gate_Close_Args, Heater_Control_Args ]

FSEP_Gate_Should_be_Open
YES
NO

Todo = [ open_FSEP_gate_valve ]

Todo = [ close_FSEP_gate_valve ]

FSEP_Gate_Should_be_Closed
YES
NO

Todo = []

Todo = [ open_FSEP_gate_valve ]

do_heater_control (Heater_Control_Args)
```

Todo = []
A. Semi-formal software specification

\[
\begin{align*}
\text{should_open_FSEP\_gate\_valve} \& \text{End}
\end{align*}
\]

\[
[\text{Signals\_From\_DDCS} = \{ \text{Remote\_Selection\_Switch} \\
\quad \text{FSTC\_Electrical\_Connectors\_are\_Engaged} \\
\quad \text{FSTC\_Pneumatic\_Connectors\_are\_Connected} \\
\quad \text{TCC\_Aligned\_at\_FSEP} \\
\quad \text{FSTC\_Coupling\_Plate\_is\_Coupled} \\
\quad \text{FSTC\_Indexing\_Mechanism\_is\_Locked} \\
\quad \text{All\_FSTC\_Drives\_are\_Switched\_OFF} \\
\quad \text{Inter\_Space\_Flushing\_Between\_FSTC\_and\_FSEP\_Completed} \\
\quad \text{FSTC\_Gate\_Valve\_Open\_Status} \}
\]

\[
[\text{Signals\_From\_Console} = \{ \text{Operator\_Selector\_Switch\_Position\_in\_Console} \\
\quad \text{FSEP\_Gate\_Valve\_Open\_Push\_Button\_in\_Console} \}
\]

\[
[\text{Signals\_From\_Panel} = \{ \text{Operator\_Selector\_Switch\_Position\_in\_Panel} \\
\quad \text{FSEP\_Gate\_Valve\_Open\_Push\_Button\_in\_Panel} \}
\]

\[
[\text{Signals\_From\_LCC} = \{ \text{Operator\_Selector\_Switch\_Position\_in\_LCC} \\
\quad \text{FSEP\_Gate\_Valve\_Open\_Push\_Button\_in\_LCC} \}
\]

\[
[\text{FSEP\_Signals} = \{ \text{Limit\_Switch\_ON\_for\_FSEP\_Gate\_Valve\_Open} \\
\quad \text{FSEP\_Gate\_Valve\_Close\_Command} \}
\]

\[
\text{Result} = ( \\
\quad \text{all\_are\_true} (\text{Signals\_From\_DDCS}) \\
\quad \text{and} \\
\quad \text{any\_one\_is\_true} (\{ \\
\quad \text{all\_are\_true} (\text{Signals\_From\_Console}), \\
\quad \text{all\_are\_true} (\text{Signals\_From\_Panel}), \\
\quad \text{all\_are\_true} (\text{Signals\_From\_LCC}) \}) \\
\quad \text{and} \quad \text{not Limit\_Switch\_ON\_for\_FSEP\_Gate\_Valve\_Open} \\
\quad \text{and} \quad \text{not FSEP\_Gate\_Valve\_Close\_Command} 
\)
A. Semi-formal software specification

should_close_FSEP_gate_valve

Result = {
    Remote_Selection_Switch_in_LCP_at_HCR_Position
    and
    CTM_Gripper_Hoist_Above_Elevation_34000
    and
    not Limit_Switch_for_Close_Status_of_FSEP_Gate_Valve
    and
    any_one_is_true ([
        all_are_true (Signals_From_Console),
        all_are_true (Signals_From_Panel),
        all_are_true (Signals_From_LCC)
    ])
    and
    not FSEP_Gate_Valve_Open_Command
}
A. Semi-formal software specification

do_heater_control

End

_Vessel_1_Thermocouples = [ Invessel_1_TCs, Outvessel_1_TCs ]
_Vessel_2_Thermocouples = [ Invessel_2_TCs, Outvessel_2_TCs ]
_Vessel_3_Thermocouples = [ Invessel_3_TCs, Outvessel_3_TCs ]
_Heater_On_Signals = [ ON_1, ON_2, ON_3 ]
_Heater_Off_Signals = [ OFF_1, OFF_2, OFF_3 ]
_Trip_Signals = [ Trip_1, Trip_2, Trip_3 ]
Soft_PID_Constants = [ _PID_1, _PID_2, _PID_3 ]
Heater_Set_Points = [ _SP_1, _SP_2, _SP_3 ]

Average_Temperature_of_Vessel_1 = average ( validate_thermocouple_set (Invessel_1_TCs) ++ validate_thermocouple_set (Outvessel_1_TCs) ),
Average_Temperature_of_Vessel_2 = average ( validate_thermocouple_set (Invessel_2_TCs) ++ validate_thermocouple_set (Outvessel_2_TCs) ),
Average_Temperature_of_Vessel_3 = average ( validate_thermocouple_set (Invessel_3_TCs) ++ validate_thermocouple_set (Outvessel_3_TCs) )

Control_Vessel_1_Heater = requires_heater_control ( ON_1, OFF_1, Trip_1, Average_Temperature_of_Vessel_1 ),
Control_Vessel_2_Heater = requires_heater_control ( ON_2, OFF_2, Trip_2, Average_Temperature_of_Vessel_2 ),
Control_Vessel_3_Heater = requires_heater_control ( ON_3, OFF_3, Trip_3, Average_Temperature_of_Vessel_3 )

Heater_Controls = [
{1, Control_Vessel_1_Heater},
{2, Control_Vessel_2_Heater},
{3, Control_Vessel_3_Heater}]

Result = [
{Heater_ID, Heater_Control, Heater_Set_Point, Soft_PID_Constant} ||
{Heater_ID, Heater_Control},
Heater_Set_Point,
Soft_PID_Constant
] <-
lists:zip3 (Heater_Controls, Heater_Set_Points, Soft_PID_Constants)

Result

End
A. Semi-formal software specification

```
average

length (list) ::= 0

YES

NO

Average = lists:sum(list) / length(list)

Average = 0

End

Validate_thermocouple_set

[Current_TCs = [ _C1, _C2, _C3, _C4, _C5, _C6 ]

Previous_TCs = [ _P1, _P2, _P3, _P4, _P5, _P6 ]]

Min = lists:min (Current_TCs),
Max = lists:max (Current_TCs)

Average_Temperature = (lists:sum (Current_TCs) - Max - Min) / 4.0

Valid_Thermocouples = [ Current_Value ||

  (Current_Value, Previous_Value) <- lists:zip (Current_TCs, Previous_TCs),
  Current_Value > 0.0, Current_Value < 500.0,
  abs (Current_Value - Previous_Value) < 5.0
]

Number_of_Thermocouples_Close_to_Average = length {

  [ TC || TC <- Valid_Thermocouples,
    abs (TC - Average_Temperature) < 10.0
  ]
}

Number_of_Thermocouples_Close_to_Average > 4

YES

Valid_Thermocouples

[]

End
```
Result = {
    Heater_is_On_Command
    and
    (not Heater_is_Off_Command)
    and
    (not Trip_Check_Back)
    and
    (Average_Temperature_of_Vessel < 593.0)
    and
    (not (Average_Temperature_of_Vessel < 603.0))
}

all_are_true
List

length ([ X || X <- List, X =:= true ]) =:= length(List)

any_one_is_true
List

length ([ X || X <- List, X =:= true ]) > 0

End
Below is the list of mutant operators used in the present study:

<table>
<thead>
<tr>
<th>#</th>
<th>Substring</th>
<th>Mutated to (separated by,)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;</td>
<td>! = , &gt;, = = , = = , = =</td>
<td>Relational operators</td>
</tr>
<tr>
<td>2</td>
<td>&gt;</td>
<td>! =, &lt;, = = , = = , = = , =</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>&lt;=</td>
<td>! =, &lt;, &gt;, = = , = = , = =</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>&gt;=</td>
<td>! =, &lt;, = = , = = , = = , =</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>!=</td>
<td>! =, &lt;, &gt;, &lt; = , &gt; = , =</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>=</td>
<td>= = , &lt; = , = 0 ^, = = , =</td>
<td>Assignment operator</td>
</tr>
<tr>
<td>7</td>
<td>=</td>
<td>= 0; // = NULL; //</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>^ , / , %</td>
<td>Arithmetic operators</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>+ , ^ , / , %</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>*</td>
<td>+ , ^ , / , %</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>/</td>
<td>% , + , ^ , -</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>%</td>
<td>% , + , ^ , -</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>+ 1</td>
<td>- 1 , + 0 , + 2 , - 2</td>
<td>Increment / Decrement</td>
</tr>
<tr>
<td>14</td>
<td>= +</td>
<td>= + 0 , = + 2</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>- 1</td>
<td>= - 0 , = - 2 , = - 2</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>24</td>
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<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td>Logical operators</td>
</tr>
<tr>
<td>34</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>= =</td>
<td>= = 0 , = = 2</td>
<td></td>
</tr>
</tbody>
</table>

**Table B.1:** List of mutant operators used in mutation testing - I
<table>
<thead>
<tr>
<th>#</th>
<th>Substring</th>
<th>Mutated to (separated by ,)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>break; / continue;</td>
<td>(<code>{ }</code>)</td>
<td>Replaces with an empty block</td>
</tr>
<tr>
<td>40</td>
<td>return</td>
<td>return 0; //, return 1; //</td>
<td>Modifies function's return value</td>
</tr>
<tr>
<td>41</td>
<td>return</td>
<td>return -1;, return NULL; //</td>
<td>*</td>
</tr>
<tr>
<td>42</td>
<td>return</td>
<td>return -1 *, return 2 *, return 1</td>
<td>*</td>
</tr>
<tr>
<td>43</td>
<td>0x0</td>
<td>0x1, 0xS, 0xA, 0xF</td>
<td>Mutates bits in constants</td>
</tr>
<tr>
<td>44</td>
<td>0x1</td>
<td>0x0, 0x5, 0xA, 0xF</td>
<td>Due to 0x0 = 0000</td>
</tr>
<tr>
<td>45</td>
<td>0x5</td>
<td>0x1, 0x1, 0xA, 0xF</td>
<td>Due to 0x5 = 0101</td>
</tr>
<tr>
<td>46</td>
<td>0xA</td>
<td>0x0, 0x1, 0x5, 0xF</td>
<td>Due to 0xA = 1010</td>
</tr>
<tr>
<td>47</td>
<td>0xF</td>
<td>0x0, 0x1, 0x5, 0xA</td>
<td>Due to 0xF = 1111</td>
</tr>
<tr>
<td>48</td>
<td>0x00</td>
<td>0x55, 0xAA, 0xFF</td>
<td>*</td>
</tr>
<tr>
<td>49</td>
<td>0x55</td>
<td>0x000, 0xAA, 0xFF</td>
<td>*</td>
</tr>
<tr>
<td>50</td>
<td>0xAA</td>
<td>0x000, 0x55, 0xFF</td>
<td>*</td>
</tr>
<tr>
<td>51</td>
<td>0xFF</td>
<td>0x000, 0x55, 0xAA</td>
<td>*</td>
</tr>
<tr>
<td>52</td>
<td>[ ]</td>
<td>[-1 +, 1 +, 0 *</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>( !, -, 1 -, 2 *, 0 *, 1 +, 1 *</td>
<td>Mutates first argument of a function</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>)</td>
<td>.1 +, .1 -, .1 *</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>)</td>
<td>.1 +, .1 -, .1 *</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>?</td>
<td>*0), *-1), *2), +1), -1)</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>unsigned / signed</td>
<td>&amp;&amp; false?,</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>int</td>
<td>signed / unsigned</td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>long</td>
<td>int, short int, char</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>float / double</td>
<td>int</td>
<td></td>
</tr>
</tbody>
</table>

Table B.2: List of mutant operators used in mutation testing - II
Data for PCA of mutant characteristics

The data for Principal Component Analysis (PCA) (Figures 5.13 to 5.15 on pages 62–64) of static analysis, dynamic analysis, and coverage impact of mutants for the all case studies is as follows:

<table>
<thead>
<tr>
<th>Using Splint</th>
<th>Killed mutants</th>
<th>Unkilled mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of mutants</td>
<td>Warnings</td>
</tr>
<tr>
<td>111</td>
<td>456</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>244</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Using Clang</th>
<th>Killed mutants</th>
<th>Unkilled mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of mutants</td>
<td>Warnings</td>
</tr>
<tr>
<td>111</td>
<td>766</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Using Cppcheck</th>
<th>Killed mutants</th>
<th>Unkilled mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of mutants</td>
<td>Warnings</td>
</tr>
<tr>
<td>111</td>
<td>765</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

Table C.1: Static analysis of FSHS mutants
### Using Valgrind

<table>
<thead>
<tr>
<th>Killed mutants</th>
<th>Unkilled mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of mutants</strong></td>
<td><strong>Warnings</strong></td>
</tr>
<tr>
<td>748</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>3102981</td>
</tr>
<tr>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td>1</td>
<td>172954</td>
</tr>
<tr>
<td>1</td>
<td>3199649</td>
</tr>
<tr>
<td>1</td>
<td>248067</td>
</tr>
<tr>
<td>1</td>
<td>5715</td>
</tr>
<tr>
<td>1</td>
<td>136773</td>
</tr>
<tr>
<td>1</td>
<td>10000000</td>
</tr>
<tr>
<td>1</td>
<td>735</td>
</tr>
<tr>
<td>1</td>
<td>36174</td>
</tr>
<tr>
<td>1</td>
<td>894604</td>
</tr>
<tr>
<td>1</td>
<td>505</td>
</tr>
<tr>
<td>(remaining) 2</td>
<td>(avg) 25366</td>
</tr>
</tbody>
</table>

### Using Coverage impact

<table>
<thead>
<tr>
<th>Killed mutants</th>
<th>Unkilled mutants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of mutants</strong></td>
<td><strong>Coverage impact</strong></td>
</tr>
<tr>
<td>142</td>
<td>0</td>
</tr>
<tr>
<td>96</td>
<td>35910576</td>
</tr>
<tr>
<td>11</td>
<td>152572</td>
</tr>
<tr>
<td>9</td>
<td>174534</td>
</tr>
<tr>
<td>8</td>
<td>1049147</td>
</tr>
<tr>
<td>6</td>
<td>360</td>
</tr>
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<td>6</td>
<td>33116832</td>
</tr>
<tr>
<td>6</td>
<td>190715</td>
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<tr>
<td>6</td>
<td>33601689</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>5</td>
<td>1009</td>
</tr>
<tr>
<td>5</td>
<td>9336</td>
</tr>
<tr>
<td>5</td>
<td>3068</td>
</tr>
<tr>
<td>5</td>
<td>37313606</td>
</tr>
<tr>
<td>5</td>
<td>33689274</td>
</tr>
<tr>
<td>(remaining) 454</td>
<td>(avg) 1076774260</td>
</tr>
</tbody>
</table>

Table C.2: Dynamic analysis of FSHS mutants
### Using Splint

<table>
<thead>
<tr>
<th>Number of mutants</th>
<th>Warnings</th>
<th>Number of mutants</th>
<th>Warnings</th>
</tr>
</thead>
<tbody>
<tr>
<td>124</td>
<td>1</td>
<td>51</td>
<td>1</td>
</tr>
<tr>
<td>99</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>3</td>
<td>2</td>
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Table C.3: Static analysis of RSU mutants
### Using Valgrind

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**Table C.4:** Dynamic analysis of RSU mutants
### Using Splint

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**Table C.5**: Static analysis of SGTLD mutants
### Using Valgrind

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### Using Coverage impact

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**Table C.6:** Dynamic analysis of SGFLLD mutants
### C. Data for PCA of mutant characteristics

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**Table C.7:** Static analysis of CTMS mutants
### Using Valgrind

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**Table C.8:** Dynamic analysis of CTMS mutants
C. Data for PCA of mutant characteristics

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### Using Cppcheck

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<td><strong>Warnings</strong></td>
<td><strong>Number of mutants</strong></td>
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<tr>
<td>209</td>
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**Table C.9: Static analysis of GES mutants**

### Using Valgrind

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### Using Coverage impact

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**Table C.10: Dynamic analysis of GES mutants**
### C. Data for PCA of mutant characteristics

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**Table C.11:** Static analysis of SGDHR mutants

**Table C.12:** Dynamic analysis of SGDHR mutants