Strong Software Reliability for Autonomous Space Robotics

Engineering The Future

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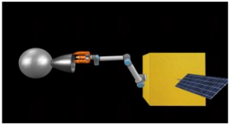
March 28, 2023

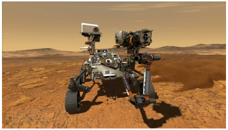
Background: Me

- PhD at Maynooth University: 2013–2017
- Postdoc at Universities of Liverpool and Manchester: 2018–2020 (FAIR-SPACE Hub)
- Postdoc at Maynooth University: 2020–2022 (VALU3S Project)
- Royal Academy of Engineering Research Fellow at The University of Manchester: 2022–2027

Engineering The Future: Moon Village

Strong Software Reliability for Autonomous Space Robotics

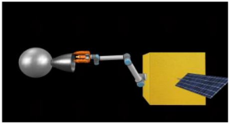


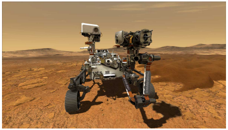


Problem:

- Space exploration necessitates the use of **autonomous** robotic systems.
- Current **verification** approaches are **not sufficient** to accurately specify the required autonomy.
- **Autonomy** introduces a unique set of concerns related to **verification** and **assurance**.

Strong Software Reliability for Autonomous Space Robotics

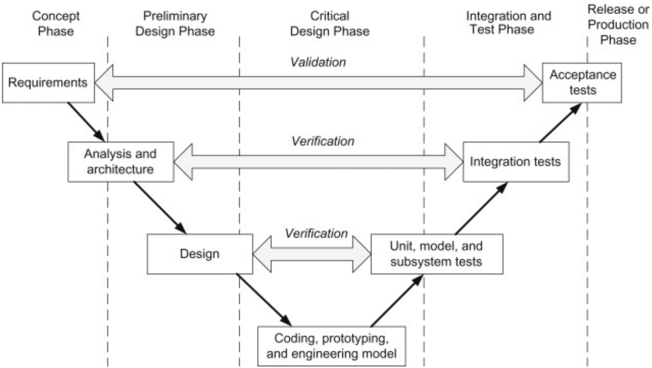


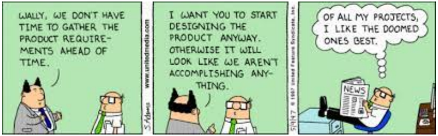


Aim:

- Devise new ways of **describing**, **analysing** and **assuring** the correct autonomous behaviour of robotic space systems.

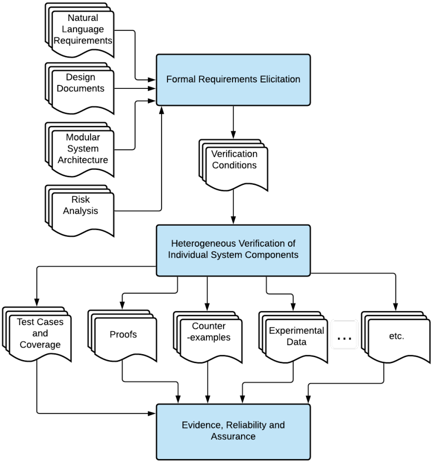
Software Development: V-Model





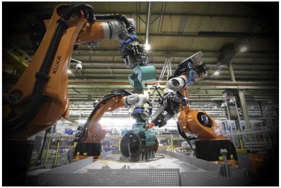
Integrating Multiple Heterogeneous Verification Techniques

- True autonomy requires a step change in **understanding** and **verification**.
- Issue of autonomous systems **assurance** remains unsolved.
- Adopt a sophisticated and **complementary** combination of robust V&V methods to support deployment in space.
- Provide formalisation of requirements for **Machine Learning** components.



Impact

This will ultimately lead to more **reliable**, more **usable** and more **effective** autonomous robots being deployed more **confidently** across a **range of sectors**.



But...

What Should I Verify?

Requirements Engineering

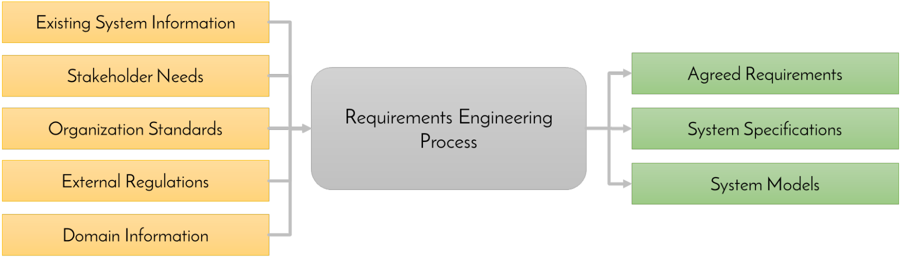
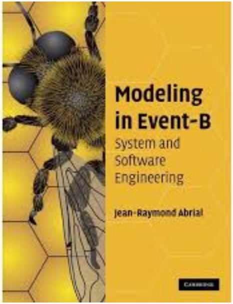


Illustration: The overall requirements engineering process

Moon Village

Requirement: Robots should always maintain a safe distance from astronauts.

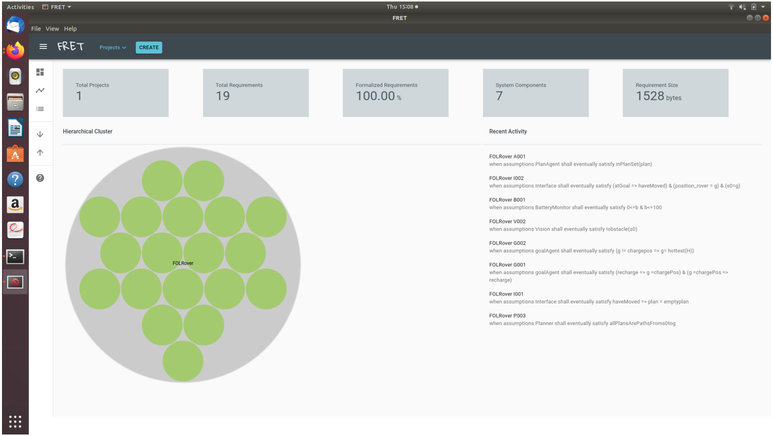
Formal Methods



What Should I Verify?

Natural Language Requirements $\neq$ Formal Properties

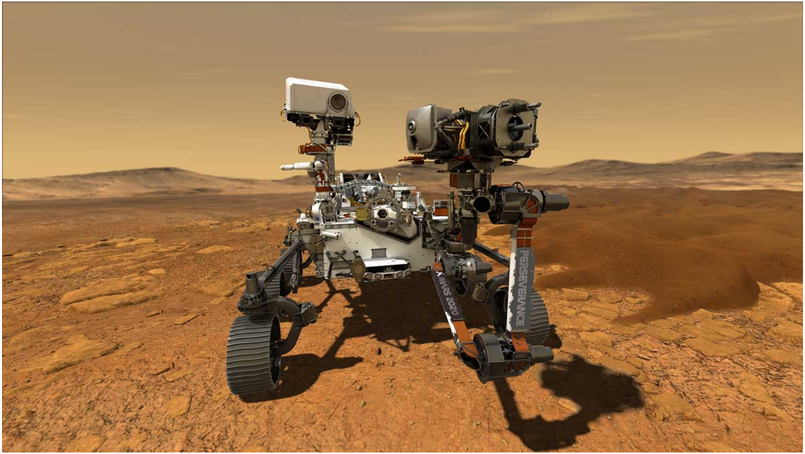
Formal Requirements Elicitation Tool (FRET)



Formal Requirements Elicitation Tool (FRET)

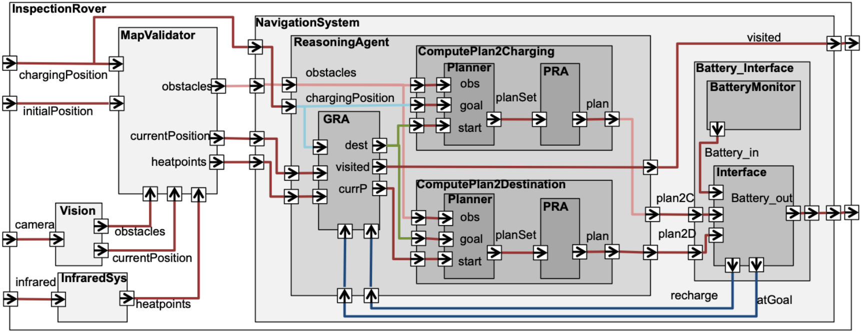
- supports the formalisation, understanding and analysis of requirements user-friendly interface
- intuitive diagrammatic explanations of requirement semantics
- users specify requirements in restricted natural language, called FRETISH, which embodies a temporal logic semantics

Example: Rover Navigation



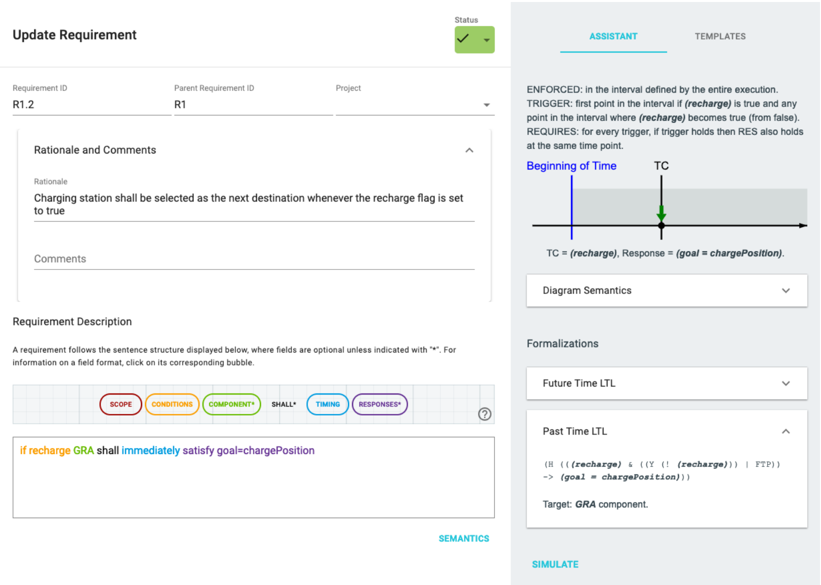
Bourbouh, H., Farrell, M., Mavridou, A., Sljivo, I., Brat, G., Dennis, L. A., & Fisher, M. *Integrating Formal Verification and Assurance: An Inspection Rover Case Study*. NFM 2021.

Rover Architecture

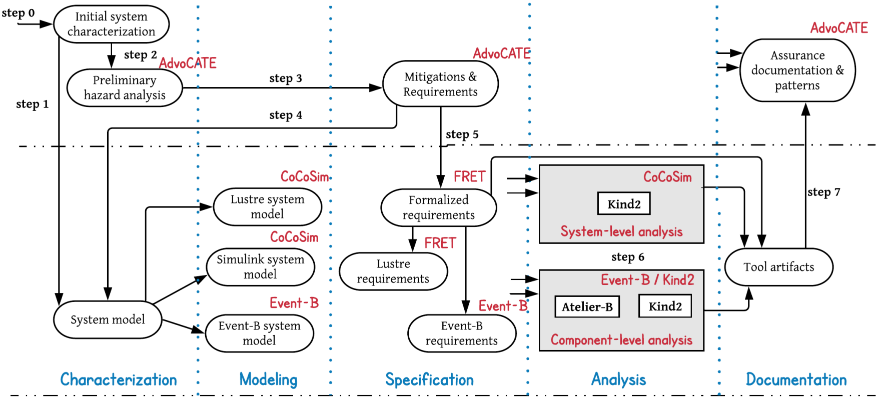


R1: The rover shall not run out of battery.
R2: The rover shall not collide with an obstacle.
R3: The rover shall visit all reachable points of interest.

Rover Requirement in FRET



Verifying Rover Navigation



Example: Aircraft Engine Controller

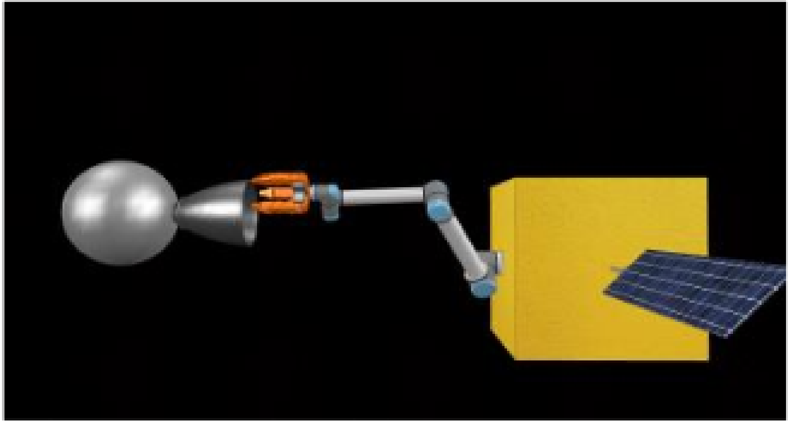
ID	FRETISH
UC5_R_1	if ((sensorfaults) & (trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_2	if ((sensorfaults) & (!trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_3	if ((sensorfaults) & (trackingPilotCommands)) Controller shall satisfy (operatingLimitObjectives)
UC5_R_4	if ((sensorfaults) & (!trackingPilotCommands)) Controller shall satisfy (operatingLimitObjectives)
UC5_R_5	if ((mechanicalFatigue) & (trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_6	if ((mechanicalFatigue) & (!trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_7	if ((mechanicalFatigue) & (trackingPilotCommands)) Controller shall satisfy (operatingLimitObjectives)
UC5_R_8	if ((mechanicalFatigue) & (!trackingPilotCommands)) Controller shall satisfy (operatingLimitObjectives)
UC5_R_9	if ((lowProbabilityHazardousEvents) & (trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_10	if ((lowProbabilityHazardousEvents) & (!trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_11	if ((lowProbabilityHazardousEvents) & (trackingPilotCommands)) Controller shall satisfy (operatingLimitObjectives)
UC5_R_12	if ((lowProbabilityHazardousEvents) & (!trackingPilotCommands)) Controller shall satisfy (operatingLimitObjectives)
UC5_R_13	if (trackingPilotCommands) Controller shall satisfy (changeMode(nominal)) | (changeMode(surgeStallPrevention))
UC5_R_14	if (!trackingPilotCommands) Controller shall satisfy (changeMode(nominal)) | (changeMode(surgeStallPrevention))

Farrell, M., Luckcuck, M., Sheridan, O., & Monahan, R. *FRETting about requirements: formalised requirements for an aircraft engine controller.* In REFSQ 2022.

What do we mean?

'***it forces you to think about the actual meaning behind the natural-language requirements***'. - *Collins Aerospace/UTRC Ireland*

Example: Active Debris Removal



Autonomous Grasping for Active Debris Removal

ID	FRET Formalisation
R1	SV shall satisfy (grasp(TGT, BGP) & closer(SV, TGT))
R1.1	Camera shall satisfy distance(Camera, TGT) $\geq$ 0.5
R1.2	TGT shall satisfy if !contact(SVA, TGT) then motionless(TGT)
R1.3	Camera shall satisfy valid(p)
R1.3.1	Camera shall satisfy maxRes(p) = 1280*720
R1.3.2	Camera shall satisfy length(p) > 0
R1.4	Imagepreprocessing shall satisfy length(filteredimage) $\leq$ length(p) & length(filteredimage) > 0
R1.5	Findoptimalgrasp shall satisfy if exists(BGP) then return(BGP)
R.1.5.1	Findoptimalgrasp shall satisfy offset(BGP, TGT) = 1 & -20 $\leq$ fingersurfaceyaw & fingersurfaceyaw $\leq$ 20
R1.5.2	findoptimallgrasp shall satisfy length(grasps) $\geq$ 0
R1.6	Findoptimalgrasp shall satisfy if !(exists(BGP)) then printerror
R1.7	Controller shall satisfy executeJointTrajectory(SVA, BGP)
R1.8	SVA shall satisfy captured(TGT) $\Rightarrow$ contactpoint(SVA, TGT) = BGP
R1.9	SV shall satisfy totalpullingdistance $\geq$ 0.3 & totalpullingdistance $\leq$ 0.5
R2	SV shall always satisfy !collide(SV, TGT)
R2.1	SV shall always satisfy !(position(SV) = position(TGT))
R2.2	SV shall always satisfy contactpoint(SVG, TGT) = BGP.
R2.2.1	SV shall satisfy if !grasped then contactpoint(SV, TGT) = null
R2.2.2	SV shall satisfy if grasped then contactpoint(SVG,TGT) = BGP + errormargin
R2.3	SVG shall satisfy captured(TGT) $\Rightarrow$ force = 180

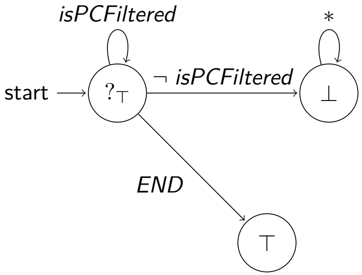
Farrell, M., Mavrakis, N., Ferrando, A., Dixon, C., & Gao, Y. *Formal modelling and runtime verification of autonomous grasping for active debris removal.* Frontiers in Robotics and AI. 2022.

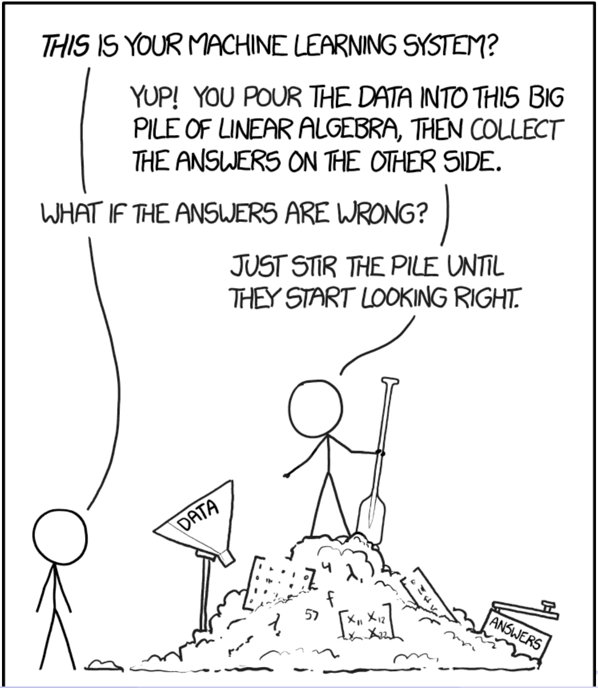
What Can We Verify?

Autonomous Grasping for Active Debris Removal

```
method imagepreprocessing(t: real , p: array<Point>, v: real , nb: int , rf: real)
  returns (filteredimage: array<Point>)
requires 0 < p.Length; // R1.3.2
requires v > 0.0;
ensures filteredimage.Length ⩽ p.Length;//R1.4
ensures filteredimage.Length > 0 ; // R1.4
{
 filteredimage := removeDepth(p,t); //remove distant points from p.
 filteredimage := downSample(filteredimage,v); / voxel representation of p.
 filteredimage := filter(filteredimage,nb,rf); //removes noise and speckles.
}
```

R1.4:




THIS IS YOUR MACHINE LEARNING SYSTEM?
YUP! YOU POUR THE DATA INTO THIS BIG PILE OF LINEAR ALGEBRA, THEN COLLECT THE ANSWERS ON THE OTHER SIDE.
WHAT IF THE ANSWERS ARE WRONG?
JUST STIR THE PILE UNTIL THEY START LOOKING RIGHT.
DATA
ANSWERS

Requirements for Machine Learning

Req ID	Requirement
[RRAV-001]	The neural network shall output the cross track distance error (perpendicular distance from the rover to the centerline.) Error to truth must not exceed X.
[RRAV-002]	Neural network shall output cross track heading error (the angle between the rover heading and the centerline.) Error to truth must not exceed X.
[RRAV-003]	Upon receiving an image, the Neural Network shall output the distance and the angle within X seconds (latency).
[RRAV-004]	Neural network shall output a sensible distance: the value must be between 0 and half the width of the taxiway plus X (buffer X so that it can still report if it is off the taxiway).
[RRAV-005]	Neural network shall output a sensible angle: the value must be between -90 and 90 degrees.
[RRAV-006]	The neural network shall achieve a minimum of X% accuracy on training and Y% accuracy on testing.
[RRAV-007]	(Local robustness) The neural network shall be robust to small perturbations in the image (pixels).
[RRAV-008]	(Semantic variations) The neural network shall be robust to irrelevant variations in the scene.
[RRAV-009]	The neural network shall safely navigate intersections.
[RRAV-010]	The magnitude of the cross track distance error shall drop below X m within T seconds and remain there.
[RRAV-011]	The magnitude of the cross track heading error shall drop below X degrees within T seconds and remain there.

Requirements for Machine Learning

Req ID	Requirement Pattern (source: NASA)
[IC-001]	The sw shall achieve an average PARAMETER value of X.
[IC-002]	The sw shall estimate PARAMETER to within $+-X$ with a $Y\%$ confidence.
[IC-003]	The sw shall estimate the confidence of the PARAMETER estimate.
[IC-004]	The requirement shall be verified by measuring the average of the parameter over N repetitions.
[IC-005]	The sw shall estimate PARAMETER with an $X\%$ confidence interval of no more than $+-Y$.
[IC-006]	The sw shall calculate the PARAMETER confidence interval at an $X\%$ confidence level.
[IC-007]	The sw shall calculate the PARAMETER as a probability distribution.
[IC-008]	The sw shall determine PARAMETER with a high level of confidence.
[IC-009]	The sw shall detect $X\%$ of occurrences of EVENT.
[IC-010]	The risk-ratio requirements shall be verified using a statistically significant set of SCENARIOS.
[IC-011]	The sw shall cause EVENT at a rate less than X times per Y DURATION.
[IC-012]	The sw shall detect CONDITION that implies EVENT is probable.
[IC-013]	The sw shall take action so that the risk ratio thresholds are satisfied.

Farrell, M., Mavridou, A. & Schumann, J. *Exploring Requirements for Software that Learns: A Research Preview.* REFSQ 2023.

Summary

- Two important questions:
  - What Should I Verify?
  - What Can I verify?
- Tools like FRET can help.
- Requirements engineering for autonomous systems is very difficult.
- Heterogeneous/corroborative verification is the way forward.

Questions?

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