2015 Flight Software Workshop, Johns Hopkins University Applied Physics Laboratory

General-purpose Payload-oriented Software Architecture for Nano-Satellites

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Introduction

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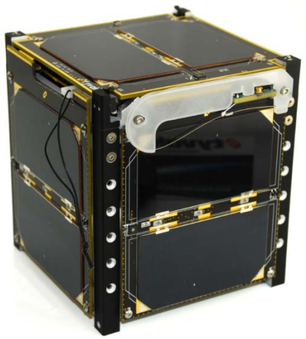
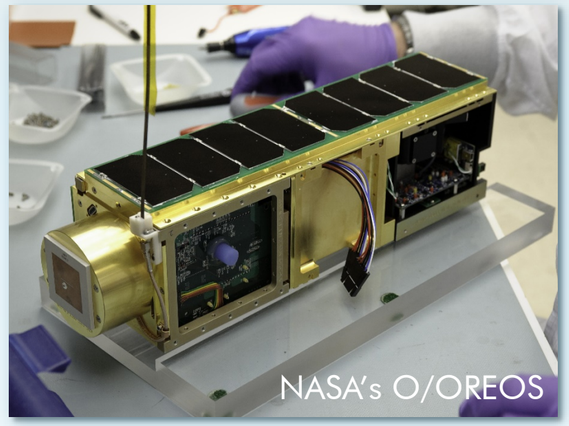


Tyvak Intrepid platform

www.nasa.gov/mission_pages/smallsats/ooreos



NASA's O/OREOS

→ Nano-satellites have become an affordable alternative for companies, research organizations and universities to access the space market.

- Either as consumers or as providers.
- Low-cost, short development times.
- Proven to be suitable platforms for:
  - technology demonstration (Bowmeester 2010);
  - a variety of EO and remote sensing purposes (Selva 2012);
  - space research (e.g. GeneSat-1);
  - and many other space applications (e.g. low-power communications, maritime activity surveillance).

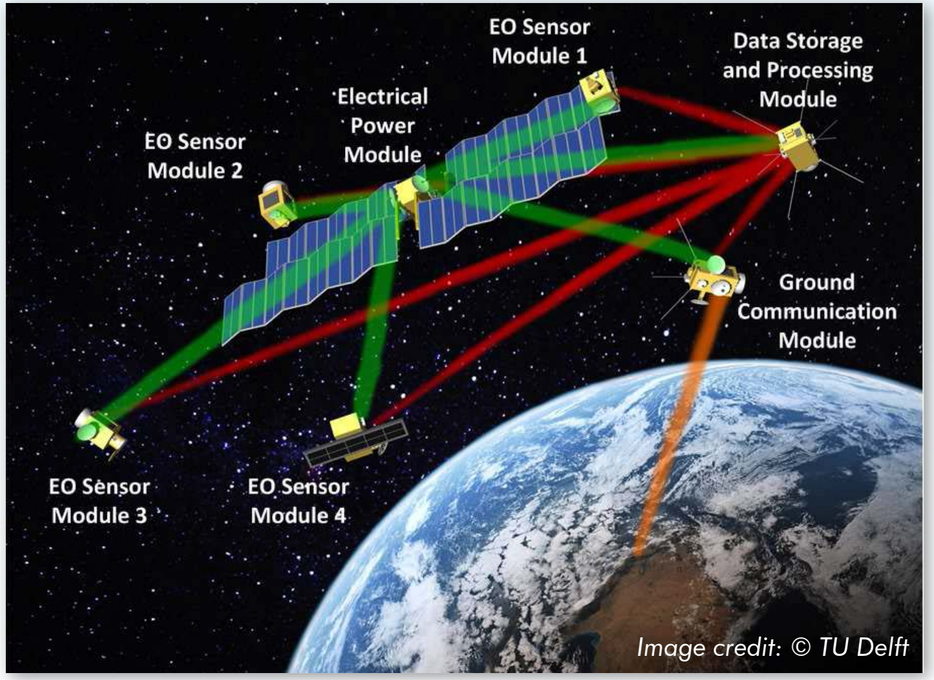
Nano-satellite programs: current context

→ Many nano-satellite missions are developed under educational programs.

- Generally less demanding in terms of accuracy and reliability.
- A clear sign of the on-going **democratization of space**.
- Continuous exploration of science return capabilities → complexity growth.

→ Nano-satellites are envisioned to be favorable for the development of new mission architectures (Banhart 2007):

- Fractionated spacecraft.
- Satellite constellations (e.g. PlanetLabs Flock).
- Federated Satellite Systems.



Nano-satellite hardware-software development

→ Integration of hardware modules/subsystems.
- Compliant with the CubeSat standard.

→ Developers ultimately need to write their custom *software* to control the spacecraft at device- and system-level.

→ Less attention has been placed on software-related issues during the consolidation of the CubeSat era.
- Software is the *final* architectural element to achieve a desired functionality.
- Software characteristics are critical for the mission → its **correctness affects the functionality** of the spacecraft.

→ Designing proper software architectures:
- Essential to achieve system-wide quality attributes (e.g. reliability, performance…)
- Should not be understood as the mere fact of writing functionally correct programs.

Presentation outline

→ This presentation addresses the issues related with the **design** of software architectures for nano-satellites.

Nano-satellite system and software characteristics	What are the critical aspects in flight sw. design?	Guidelines for nano-satellite software design.	Illustrated with an software architecture.
✓ *Extracted from successful missions and the literature.*	✓ *Software qualities.* ✓ *System requirements.* ✓ *Where developers should focus?*	✓ *Generic; mission-agnostic.* ✓ *Applicable both in educational and industry contexts.* ✓ *Our contribution to address critical aspects.*	✓ *The ^{3}Cat-1 software architecture.*

Presentation outline

Nano-satellite system and software characteristics

- ✓ *Extracted from successful missions and the literature.*

What are the critical aspects in flight sw. design?

- ✓ *Software qualities.*
- ✓ *System requirements.*
- ✓ *Where developers should focus?*

Guidelines for nano-satellite software design.

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Illustrated with an software architecture.

- ✓ *The ^{3}Cat-1 software architecture.*

Nano-satellite system characteristics

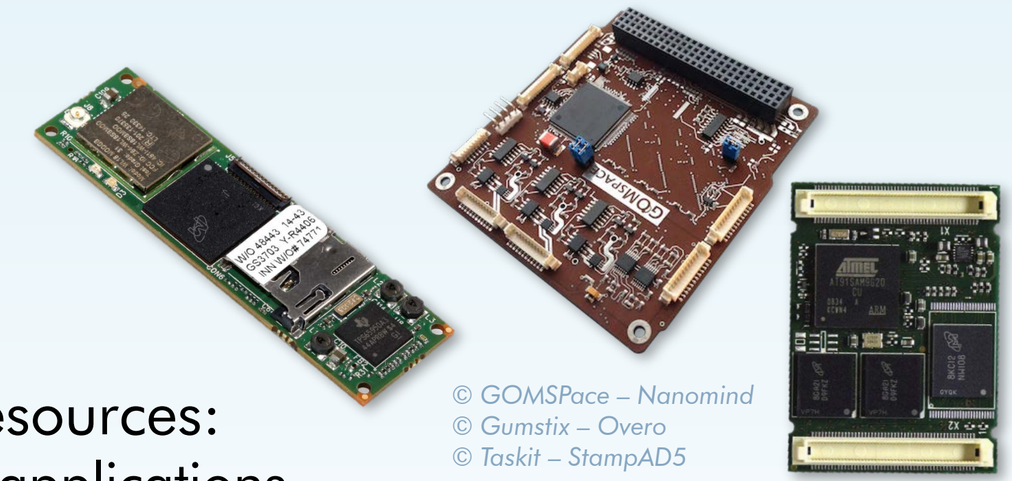
→ Reusable platforms:
- The same platform is used for several generations within the same nano-satellite program.
- Low-cost.
- Fast development cycles.

→ COTS components:
- Non-rad-hard technology.

→ No hardware redundancy.

→ Limited power availability.

→ On-board computers with very low computational resources:
- Single-Board Computer modules (SBC) for embedded applications.
- ARM CPU, 40~500 MHz.
- ~256 MB of RAM or less (e.g. GOMSpace's NanoMind: 4 MB).



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→ Constrained communication links.

→ Usually LEO orbits.

→ Ground-operated: time-tagged commands are uplinked and executed sequentially.

Nano-satellite software characteristics

→ Many approaches to improve system reliability:

- Process isolation and protected memory areas.
- Real-Time Operating Systems: small footprint, soft-real-time Linux kernels.
- FDIR methodology: ESA's OPS-SAT CubeSat, TU Delft's DelFFi (Bräuer 2015).
- Software redundancy: triplicate critical data.
- Robust communications: prevent unreliable delivery of digital data.
- Hardware and software-watchdogs.
- …

→ Some approaches towards modularity and updateability.:

- Dynamically-linked libraries: encapsulate re-usable components.

→ Architectural diversity:

- Centralized: e.g. CalPoly's 2nd Gen. Bus (Manyak, 2011).
- Decentralized/distributed: e.g. AAUSAT3 software (Bønding 2008).

Presentation outline

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Illustrated with an software architecture.

- ✓ *The ^{3}Cat-1 software architecture.*

Requirements for next-generation nano-satellite software

→ Where should software engineers focus?

1. Robustness → software quality.
2. Software modularity and scalability → software quality.
3. Autonomy → functionality.

→ Fundamental for nowadays' nano-satellite software.

→ **ROBUSTNESS:**

Large spacecraft:

- ✓ Rad-hard components to help mitigate SEU and SEL.
- ✓ Sophisticated real-time kernels, hypervisors and middleware with flight heritage (e.g. cFS/cFE.)

Nano-satellites:

- SEU and SEL are critical (use of COTS and tightly constrained power budgets).
- Some can be adopted, although they are usually unknown (especially in university programs). Engineers tend to use other alternatives (e.g. FreeRTOS, std. Linux…)
- *Designing* robustness is critical (at an architectural level too.)

Requirements for next-generation nano-satellite software

→ The capabilities of satellite constellations consisting of many (identical or *heterogeneous*) nano-satellites are promising.

→ Unceasing technology miniaturization is allowing new, smaller, less power demanding and more capable devices and modules potentially increasing the payload capacity of nano-satellites.

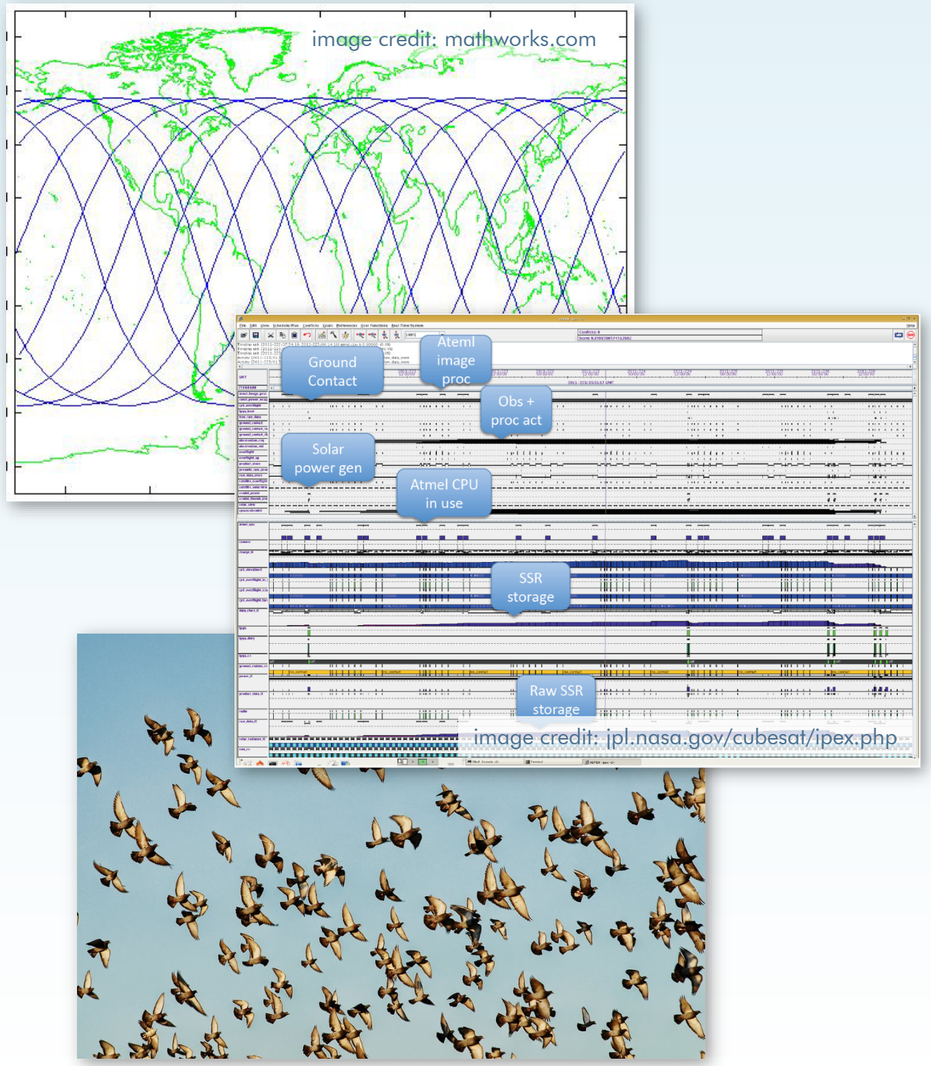
→ Due to their low cost, nano-satellite platforms are usually reused. New generations of nano-satellites have the same basic subsystems but host different payloads.

MODULARITY AND SCALABILITY:

- **Flexible** architectures: easy to update/port when the underlying hardware changes.
- **Scalable and modular** in terms of payload functionality (i.e. payload management capabilities)
- Easy to maintain and fix.

Requirements for next-generation nano-satellite software

→ AUTONOMY:



→ Limited observability:
- Constrained communication links:
  - Usually in the UHF band.
  - Limited telemetry data rates/volume.
  - Downloading fine-grained state history is unfeasible.
- LEO orbits: ~5-8 passes per day; ~10 minutes each.
- Need to be able to autonomously recover from errors and re-plan its activities.

→ On-board data analysis improves science return (e.g. NASA's EO-1: CASPER)
- Higher computational capabilities are required.
- In nano-satellites, e.g. IPEX (CASPER).

→ New mission architectures demand unit-autonomy:
- Nodes need to proactively cooperate (communicate, exchange resources) to achieve global common goals.

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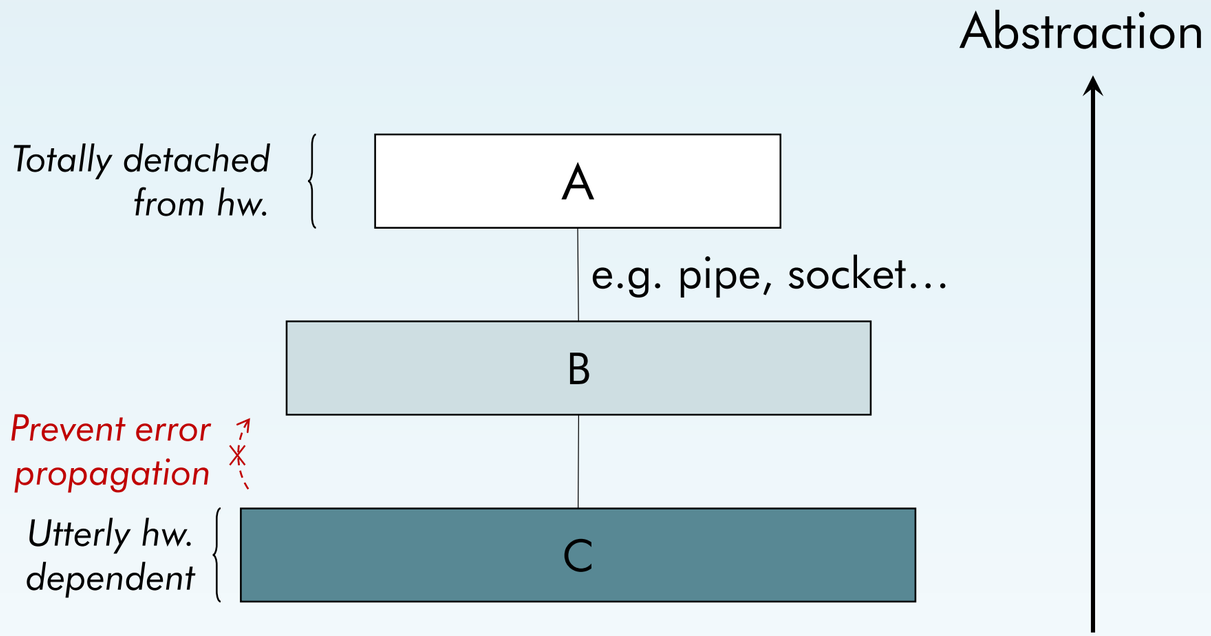
Illustrated with an software architecture.

- ✓ *The ^{3}Cat-1 software architecture.*

Design guidelines for nano-satellite flight software

→ *Robustness through hierarchy*:

- Boosts robustness from a purely architectural standpoint.
- Abstract/generic approach: logical ordering of components.
- Based on encapsulation and goal-oriented decomposition of functionalities.

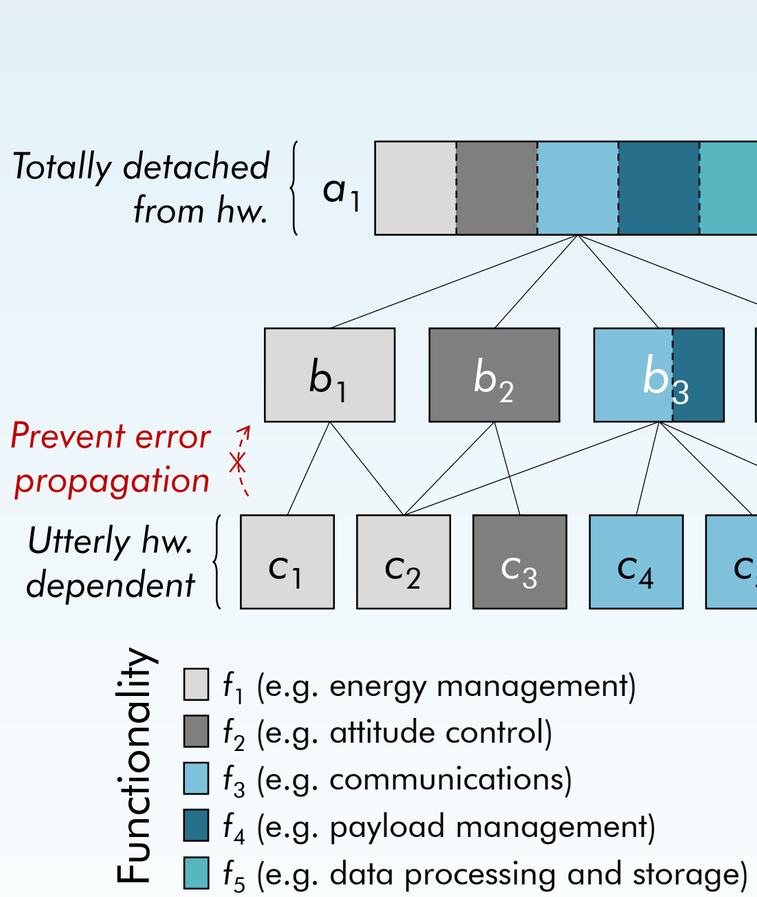


- Abstraction layers: top ones are implement high-level functionality and do not rely on hardware (devices, buses, subsystems.)
- Each layer interacts with its adjacent levels:
  - Decompose (encapsulate) actions: commands, tasks, routines, functions…
  - Hierarchical relationships through robust communication channels (e.g. IPC, ITC…)
  - If modules are sufficiently isolated: removal of error propagation paths.

Design guidelines for nano-satellite flight software

→ *Robustness through hierarchy*:

- Horizontal fragmentation based on functionality.
- Functionalities are disseminated across levels of abstraction.
  - Minimizes complexity of each component.
- From high-level (very abstract) goals to low-level (close to hardware) goals.
- High-level (critical) are detached from hardware sources of error. E.g.:
  - Subsystem's power failure.
  - File system failure.
  - Payload failure.



functionalities are much more intertwined

Abstraction

Start high-level tasks, set mission constraints, trigger system states, validate sensor data with models.

Manage active processes/threads, expand states, decrypt telemetry commands, manage subsystems.

Send commands to devices, enable power regulators, log scientific data.

Illustrative goals

Design guidelines for nano-satellite flight software

→ *Payload-oriented modularity*:

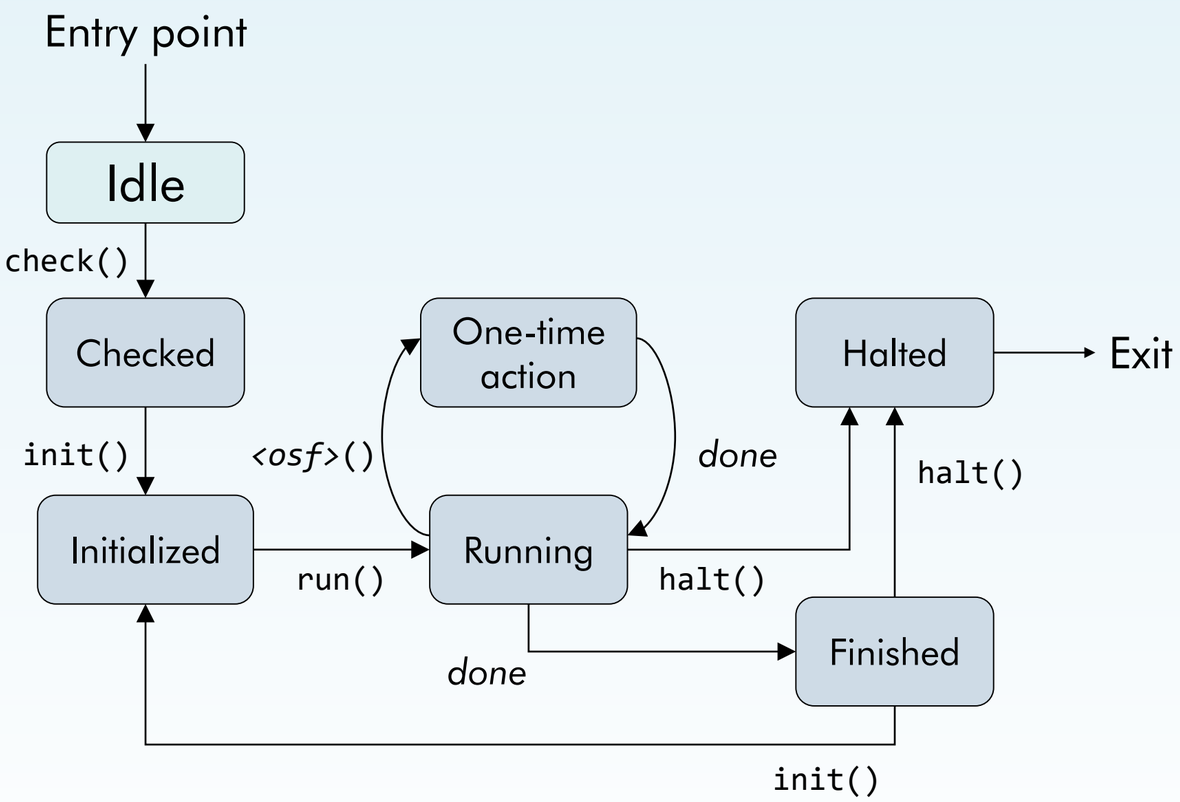
- Identifying the subsets which maximize internal coupling and minimize coupling between modules is a demanding intellectual exercise influenced by subjectivity.

- To achieve reusability, maintainability and flexibility: proper modularization should:
  - Identify what parts of the system are likely to change.
  - Locate those parts (i.e. their functionality) in specialized components.
  - Design inter-module interfaces that are insensitive to the anticipated changes, preventing the changeable aspects to be revealed by the interface.

- Changeable parts:
  - Subsystems: they are not removed, but can change (EPS, ADCS, COM…)
  - Payloads hosted by the spacecraft will differ from one mission to another.

Design guidelines for nano-satellite flight software

→ *Payload-oriented modularity*:



Generic FSM for payload/subsystem modules.

- Common interface for all low-level modules (subsystem and payload control.)
- Interface: set of functions that can be invoked outside the module, namely:
  - `check()` – Verify that the subsystem does not present any error. Runs unit tests and reports issues.
  - `init()` – Cleanly initializes subsystem/payload and acquires static resources (e.g. memory, DB connection, starts peripheral's drivers…)
  - `run()` – Executes routines.
  - `halt()` – Resets all system variables and devices, releases resources and exits.
  - One-shot functions – Interrupts or duplicates execution thread, to retrieve instantaneous data (e.g. sensors), trigger internal state transition or to perform one-time actions (e.g. enable DC/DC.)
    - The list of OSF is custom to each module.

Design guidelines for nano-satellite flight software

→ *Towards autonomous spacecraft*:

Ground-segment-operated: time-tagged telemetry commands are uploaded at each pass. Task schedule is generated by ground-segment.

Change in the operability paradigm

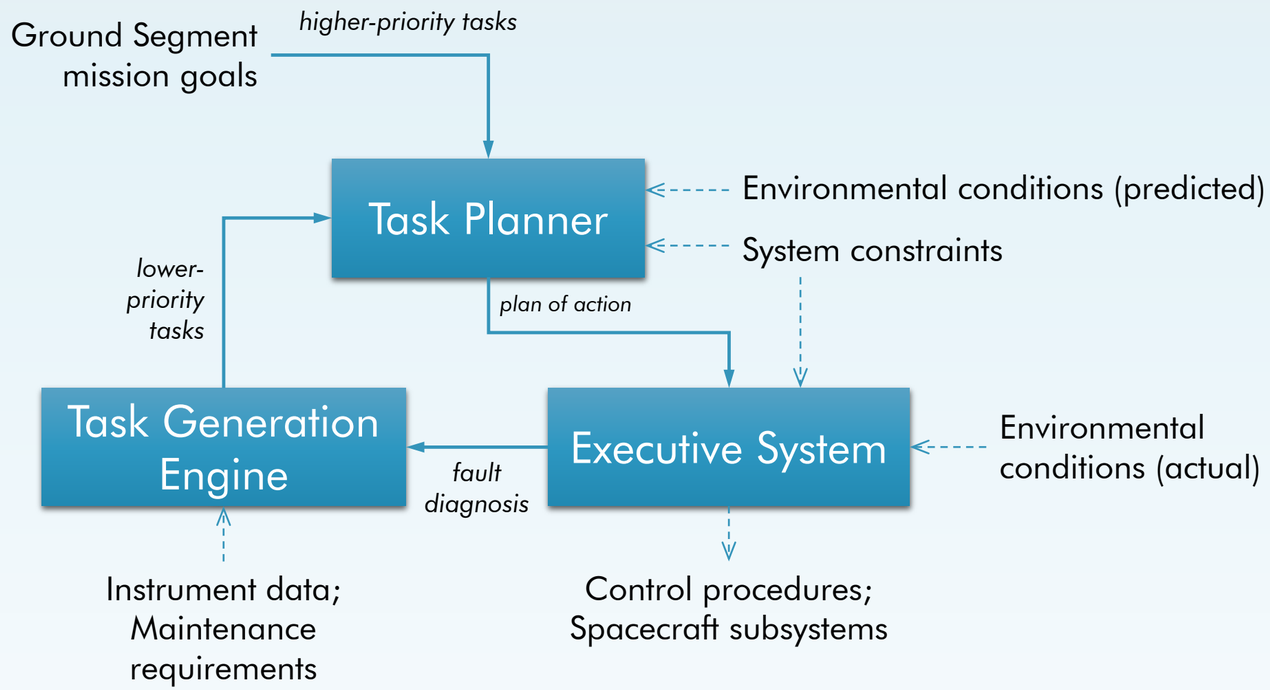
Autonomous spacecraft. Mission operators upload/update mission goals. Tasks are scheduled on board.

- Providing autonomous mission planning capabilities.
- Concept initially explored by NASA'S DS-1 RAX.
- Autonomy system:
  - Ability to intelligently ***plan*** activities.
  - Ability to robustly ***execute*** this plan.
  - Based on mission goals (e.g. study crop evolution, capture images of volcano eruptions), deterministic environmental conditions (e.g. orbit position, input power) and system constraints (e.g. battery state-of-charge.)

Design guidelines for nano-satellite flight software

→ *Towards autonomous spacecraft*:

- Architectural approach: *3 essential components* to design an **Autonomy System**.
- Task Planner:
  - Collects high-level goals → tasks.
  - Schedules system resource allocation for their execution (e.g. memory, storage, power.)
  - Could prioritize tasks.
- Executive System:
  - Decomposes plan of action.
  - Perform all procedures to achieve it.
  - Monitors constraints are not violated.
- Task Generation Engine:
  - Advanced/optional component.
  - On-board instrument data analysis to trigger task generation.
  - Checks system state and proposes maintenance tasks (e.g. reaction wheels desaturation, database maintenance.)



- Inflicts severe computational burden (CPU time, memory, power).
- Forces parts of the Autonomy Sys. to be enabled intermittently (scheduler).

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Guidelines for nano-satellite software design.

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- ✓ *Our contribution to address critical aspects.*

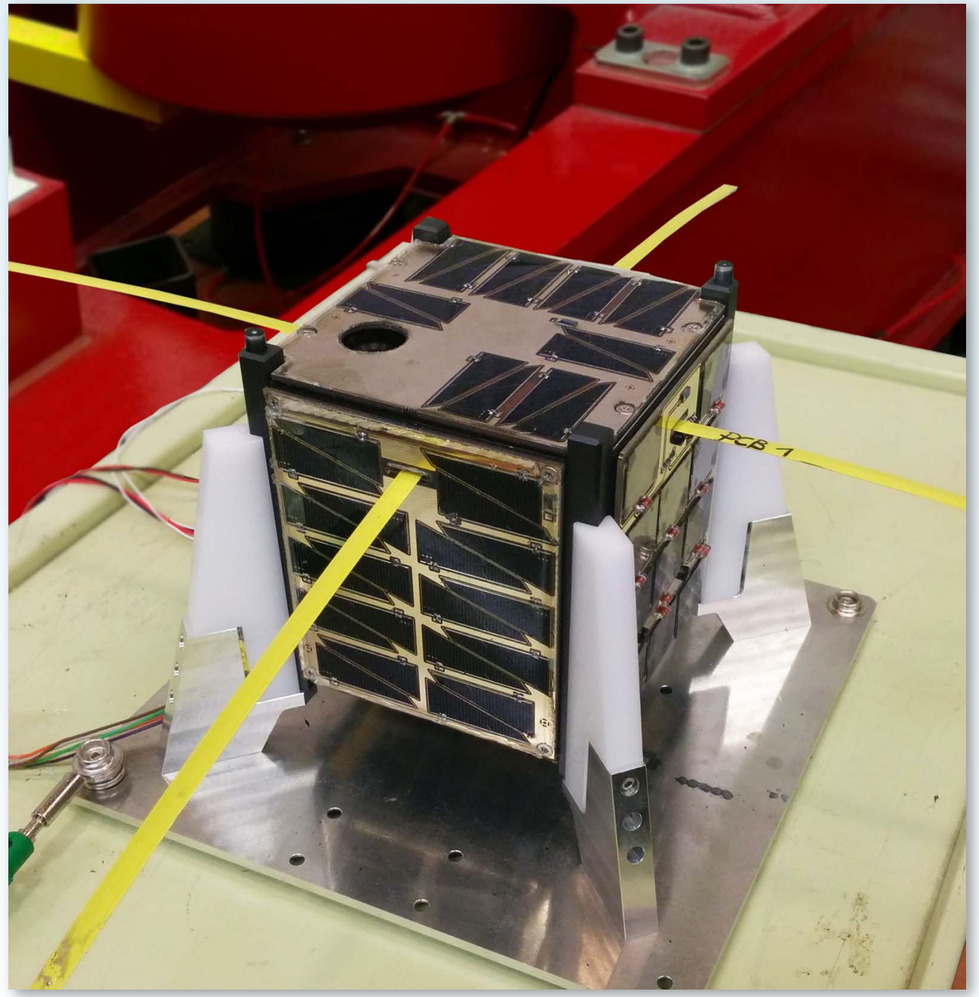
Illustrated with an software architecture.

- ✓ *The ^{3}Cat-1 software architecture.*

Applying design criteria: mission context

→ The CubeCAT (^{3}Cat) program:

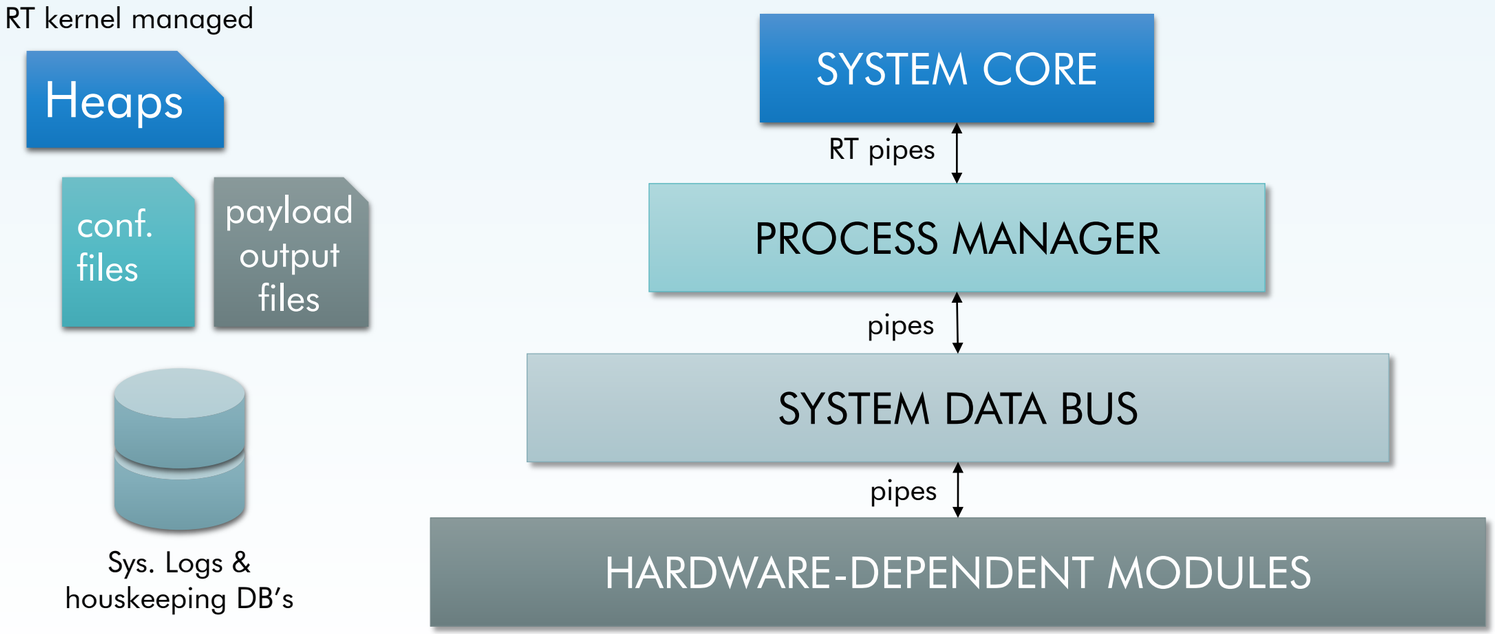
- Nano-Satellite and Payload Laboratory at UPC BarcelonaTech.
- ^{3}Cat-1:
  - Technology demonstrator mission.
  - Explore the payload capacity of a 1U CubeSat.
  - 7 payloads
    - Visible low-resolution CMOS camera.
    - Geiger counter based on COTS module.
    - CellSat: silicon Solar Cells.
    - Graphene Transistor characterization.
    - Wireless Power Transfer experiment.
    - MEMS-based atomic oxygen detector.
    - Self-powered beacon based on energy-harvesting techniques.
  - OBC: AT91SAM9G20, ARM7 at 400 MHz, 64 MB.
- Test campaign in its last stage.
- Spacecraft delivery in December 2015, launch tentative date Jan-Mar 2016.
- ^{3}Cat-2, ^{3}Cat-3 currently in development.



Applying design criteria: ^{3}Cat-1 software architecture

→ OS:
- Xenomai 2.6.2.1 + Linux kernel 2.6.35.9 (RT hypervisor approach).
- Software architecture deployed as non-real-time processes, and real-time tasks.

→ Four-tiered architecture:
- Inter Process Communication based on RT-pipes, RT-heaps, regular pipes, files and SQLite3 databases.



High-level system state control (global FSM), Energy states, Autonomy System (Task Planner)

System Executive: state expansion, high-level task decomposition (into processes, routines, etc.)

Command forwarder system. Transparent interface between Procman and HWmod.

Low-level payload and subsystem controllers. Encapsulated with a general purpose interface.

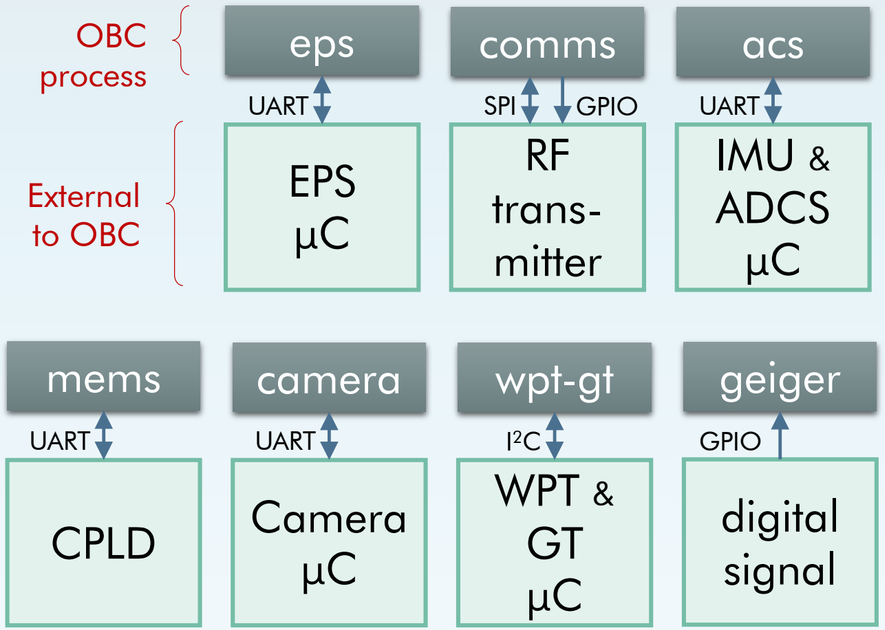
Applying design criteria: ^{3}Cat-1 software architecture

→ Hardware-dependent modules (HWmod):
- Encapsulation of payload and subsystem functionality → 7 processes with the same interface.

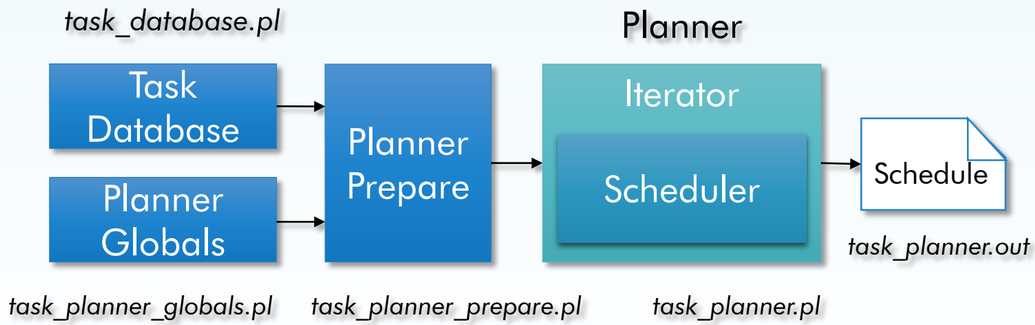
→ System Data Bus (SDB):
- A transparent, reliable and secure interface to low-level processes.
- Ad-hoc protocol:
  - 34 commands (4 to control process FSM and 30 OSF)
  - 7 control frames (ACK, asynchronous notifications…)

→ Process Manager (Procman):
- A robust *multi-threaded* executive.
- Executes high-level actions. Decomposes mission tasks into a set of sequential actions.
- Manages low-level process states.

→ System Core (Syscore):
- Monitors system vitals/variables: state-of-charge, temperatures, power input, latch-up's.
- Implements high-level (system) Finite State Machine.
- Encompasses a **Fully elastic, priority-based, multi-resource task planner**.



List of HWmod processes and hardware components



Task Planner components (implemented in Prolog)

Conclusion

→ Current nano-satellite trends have not focused on software issues.
- Nano-satellite designs have explored many techniques and designs to improve the spacecraft functionality, and system-wide qualities.

→ Due to the current context, three design areas can be improved: robustness, modularity oriented to payloads, spacecraft autonomy.
- Some of these have been extensively explored for large satellites.
- Nano-satellites can be an essential element in complex architectures and also require the exploration of software design techniques and architectural approaches.

→ Three design guidelines are proposed:
- Generic: mission-agnostic, applicable in educational and industrial programs.
- Proper encapsulation and hierarchy of components.
- Re-usable architectures; payload/subsystem modularization & interface definition.
- Nano-satellites may also benefit from autonomous capabilities.
  - Change of paradigm: from command-based to goal-oriented.
  - An enabler for nano-satellite constellations.
  - Reduced observability and bandwidth requires intelligent instrument control.
  - Computational requirements are critical and will determine the availability of such systems.

Thanks for you attention

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Backup slides

Nano-satellite software techniques and designs

→ Process isolation and protected memory.
- UNIX process model instead of TSP kernels/middleware.

→ Real-Time Operating Systems:
- Critical to avoid priority inversion, deterministic execution of critical tasks…
- Instead of using industry renowned products (i.e. VxWorks, RTEMS, QNX, LynxOS, …) nano-satellite developers tend to prefer free/open-source alternatives.
  - Small-footprint: FreeRTOS, uC/COS-III…
  - Soft-real-time Linux: PREEMPT_RT, Xenomai, uCLinux.

→ FDIR methodology:
- E.g. ESA's OPS-SAT CubeSat: dedicated FDIR computer that monitors each payload through modular controller.
- Despite complex FDIR systems requiring high computational capabilities, some nano-satellite programs have analyzed fault trees, and designed procedures to circumvent errors. E.g. TU Delft's DelFFi (Bräuer 2015).

Nano-satellite software techniques and designs

→ De-embeddable core:

- CalPoly's 2nd Gen. Bus (Manyak, 2011)

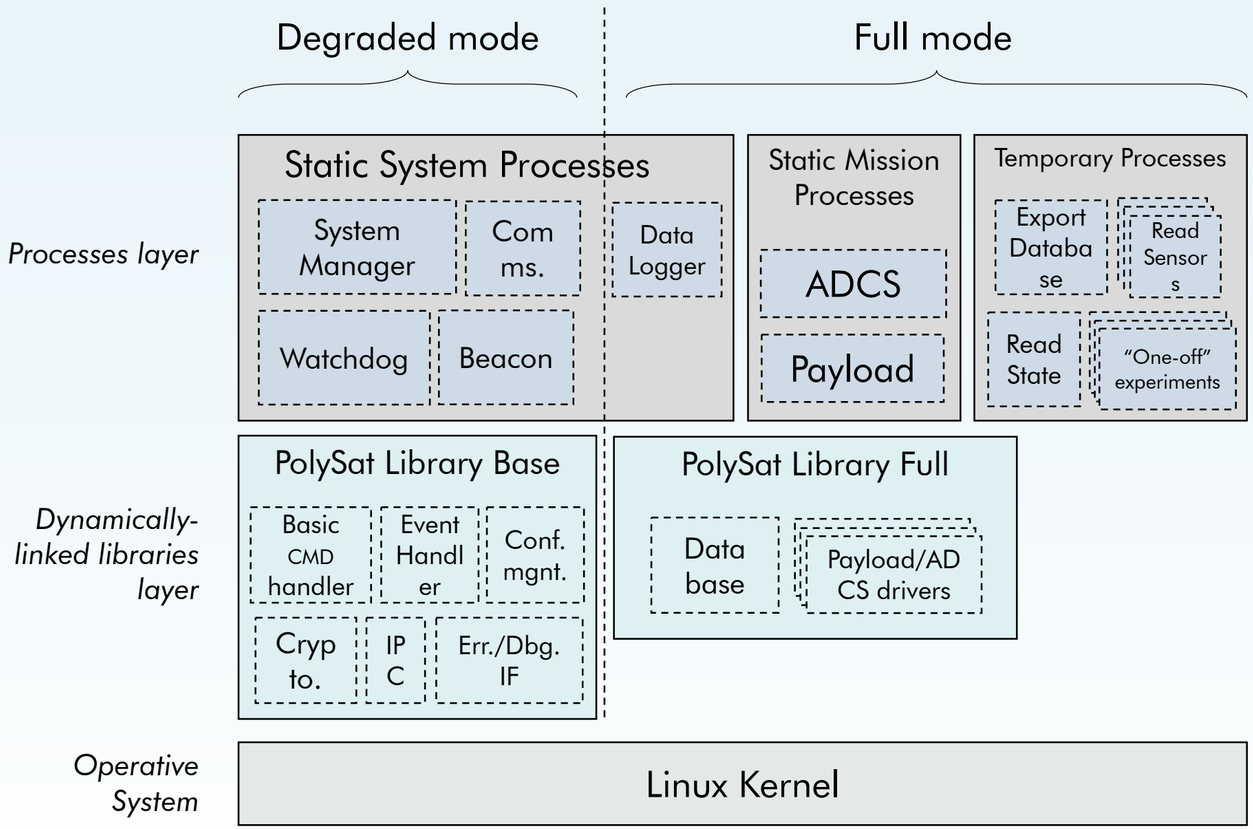
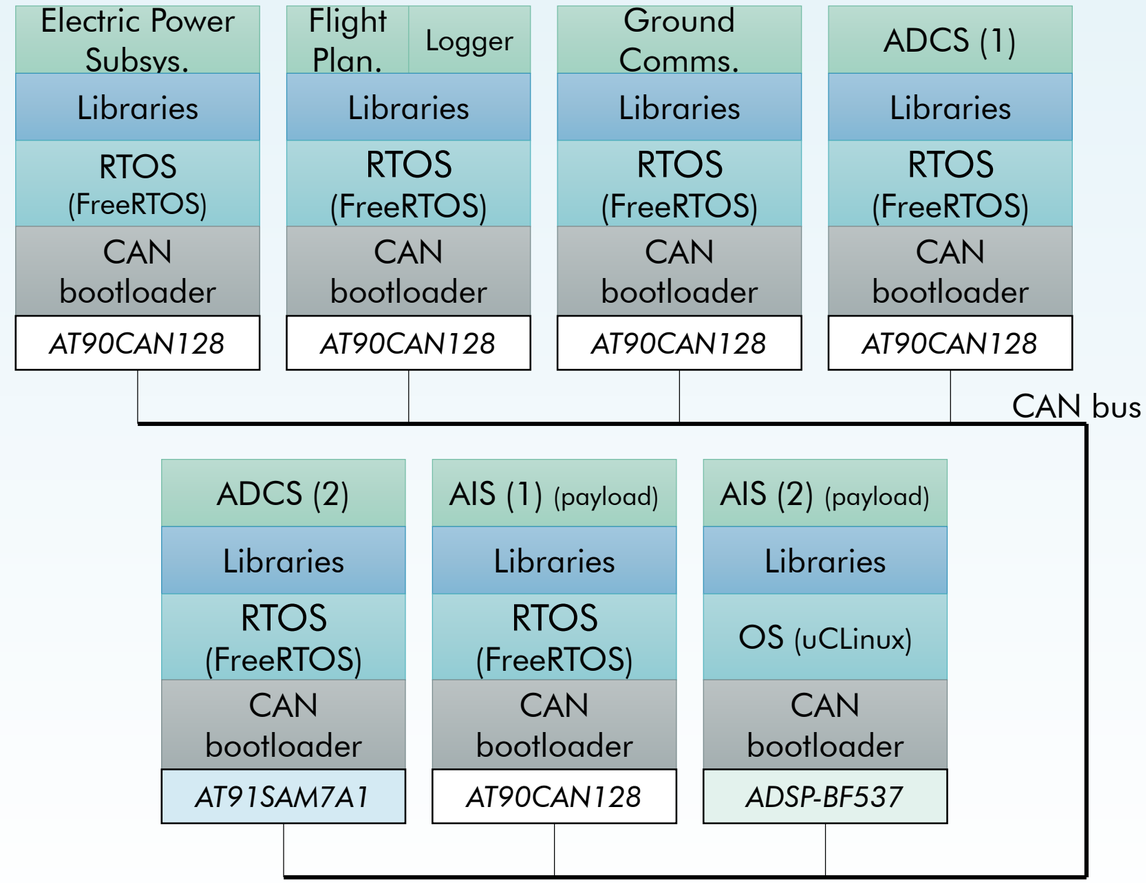


Diagram extracted from Manyak 2011, and adapted

→ Decentralized/distributed approaches:

- AAUSAT3 software (Bønding 2008)



Nano-satellite software techniques and designs

→ Dynamically-linked libraries.
- Reusable code/segmented software: easy to update/maintain.

→ Software redundancy:
- Data redundancy: triplicate critical data (e.g. config. params.) in EEPROM (Hishmeh 2009).
- Bootloader redundancy: triplicate kernel images in NAND.

→ Other techniques:
- Robust communications:
  - Prevent unreliable delivery of digital data (over digital buses, e.g. SPI, I^2C, CAN…)
  - Error Detection and Correction techniques (EDAC): data integrity checks, Ack/Nack, Handshakes, timeouts…
- Hardware and ***software*** watchdogs:
  - Restart modules when unexpected deadlocks happen.
  - Process heartbeat (between components; also among different CPU's)
- Robust programming.
  - Strict coding rules.
  - When applying industry standards for software reliability is too complex or unfeasible, adopt simpler alternatives: *G. J. Holzmann "The power of 10: rules for developing safety-critical code" (NASA/JPL Laboratory for Reliable Software)*

Requirements for next-generation nano-satellite software

→ Assessing the goodness of the software is fundamental to understand the system's strengths and weaknesses.

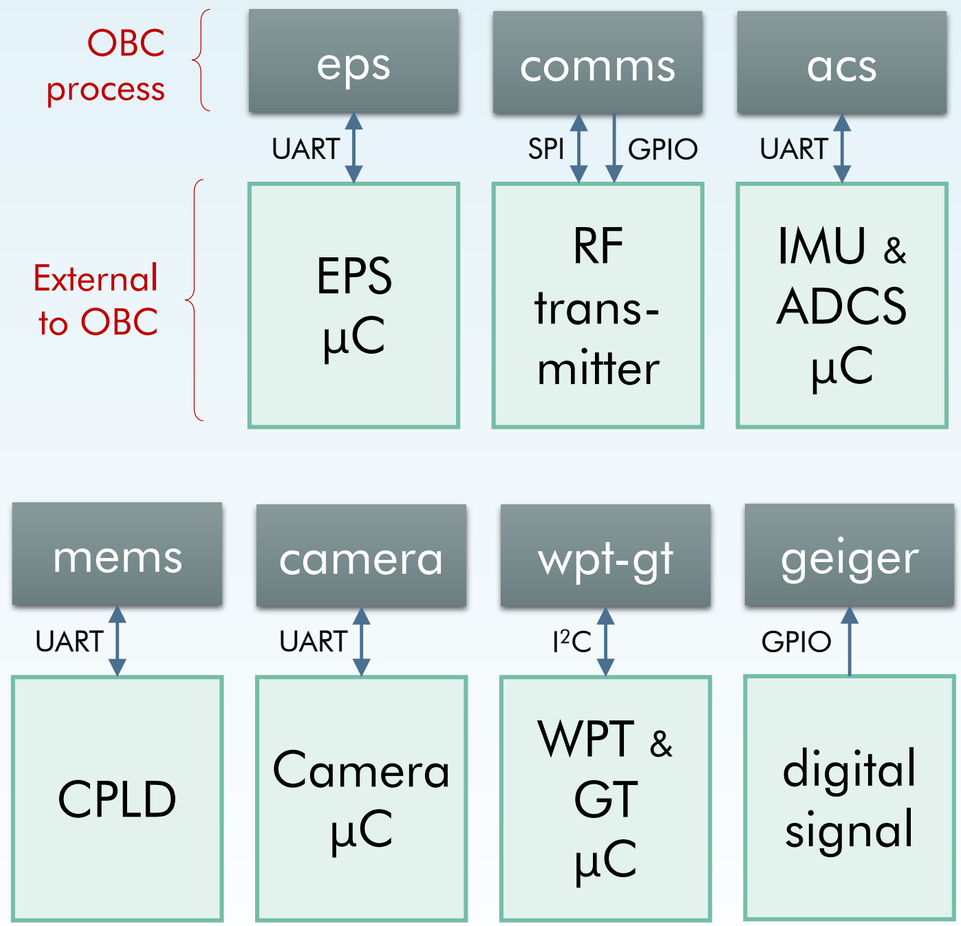
→ Software quality: "The degree to which the software possesses a desired combination of quality attributes" (IEEE Std 1061-1992).

- Quality attributes:
  - Non-functional requirements.
  - Intertwined with each other:
    reliability ↔ performance ↔ portability, …
  - *Orthogonal* to the software functionality.
- Each quality attribute should be weighted in the context of system-specific goals.
- **Subjective** assessment:
  - The list of attributes is diverse.
  - Units or numerical representation are usually not defined.

Applying design criteria: ^{3}Cat-1 software architecture

→ Hardware-dependent modules (HWmod)

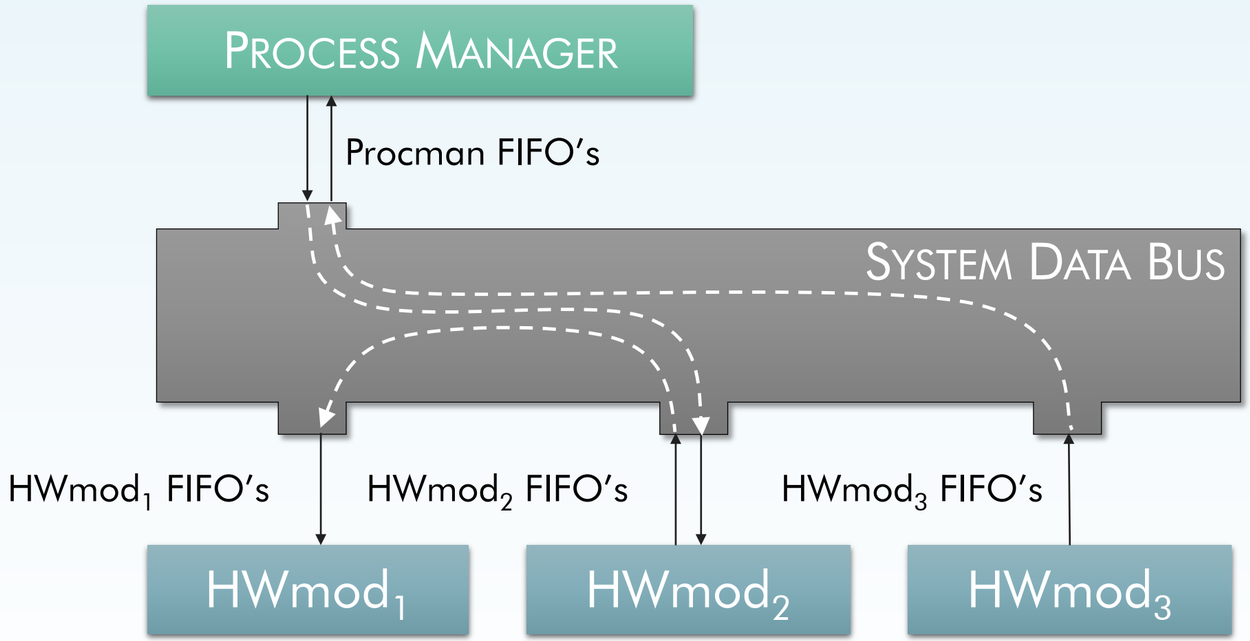
- Subsystem HWmod:
  - EPS → Controls power management board, performs housekeeping.
  - ACS → Interfaces attitude control and determination board.
  - Comms. → Implements comms. protocol and delivers telemetry commands to the system.
- Payload HWmod:
  - MEMS, Camera, Geiger, WPT-GT → perform experiment/demonstration by interacting with the dedicated board and devices.
- All of them implement a common interface (`check()`, `init()`, `run()`, `halt()` and 22 one-shot functions.)
- Each process is configured with a set of `PARAM=<value>` pairs defined in their configuration files.
- Processes start and remain in idle until a command arrives. If an error occurs, they are automatically restarted by the architecture.



Applying design criteria: ^{3}Cat-1 software architecture

→ System Data Bus (SDB)

- Transparently, reliably and securely forward commands and data (accounting for command permission level).
- Encapsulates/hids low-level architectural structure and components.

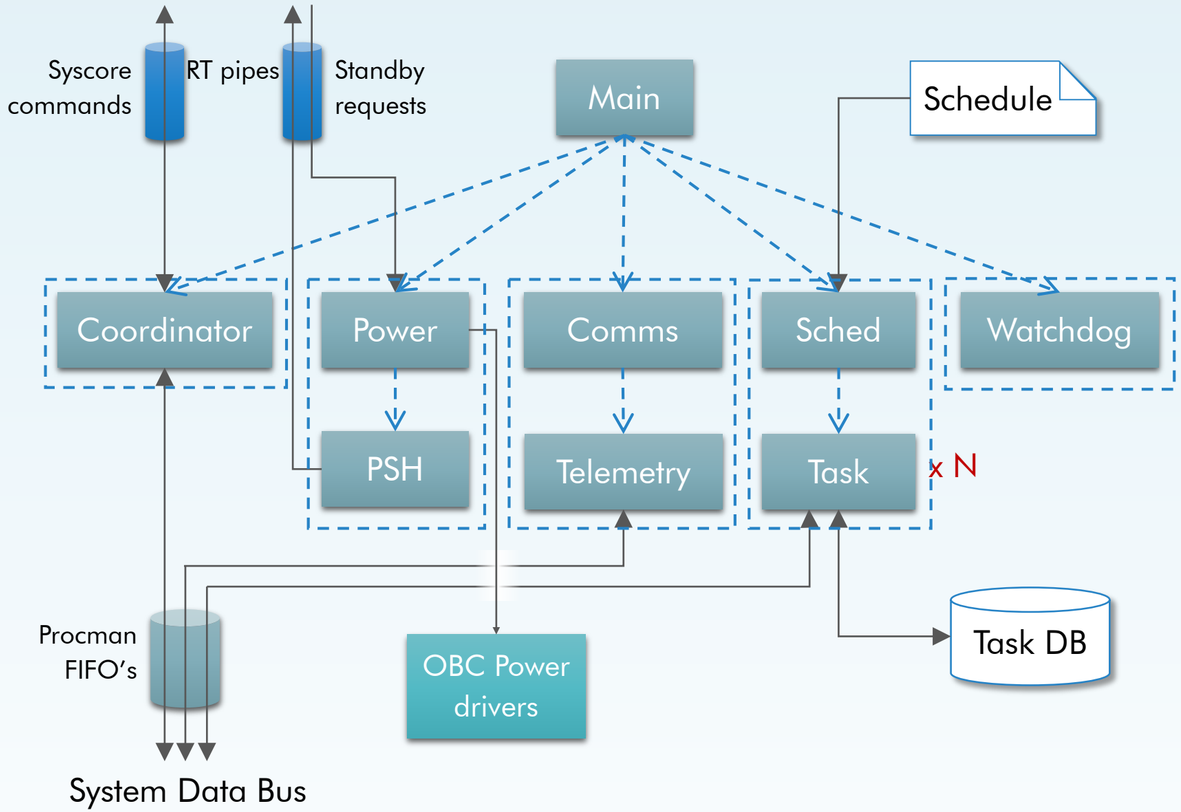


- Implements a custom protocol:
  - 34 commands (4 to control process FSM and 30 OSF)
  - 7 control signals (ACK, asynchronous notifications…)
- SDB v2
  - Modular Command System → parametrized definition of mission commands: fixed at compile-time.
  - SDB is a common command interface for all architectural levels.
  - Multi-Level Security domains can be defined to protect critical/system commands.

Applying design criteria: ^{3}Cat-1 software architecture

→ Process Manager (Procman)

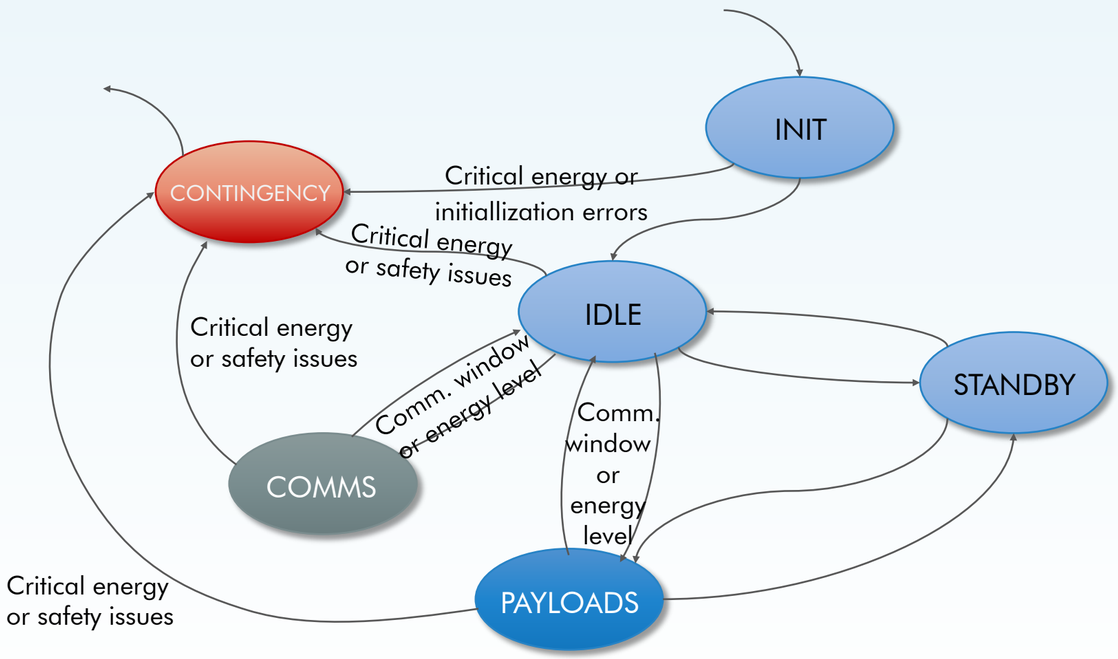
- A robust multi-threaded executive.
- Executes high-level actions.
  - Runs system states triggered by the Syscore.
  - Notifies subsystem failures (resulting from `HWmod.check()` invocations or from asynchronous signals.
- Decomposes mission tasks into a set of sequential actions.
  - Defines and executes task handler routines.
  - Plan of action defined by Syscore in the schedule file.
- Manages low-level process states.
  - Through the SDB protocol.
  - Writes/checks module parameters to configuration files.
- Interacts with the kernel to control OBC power states.

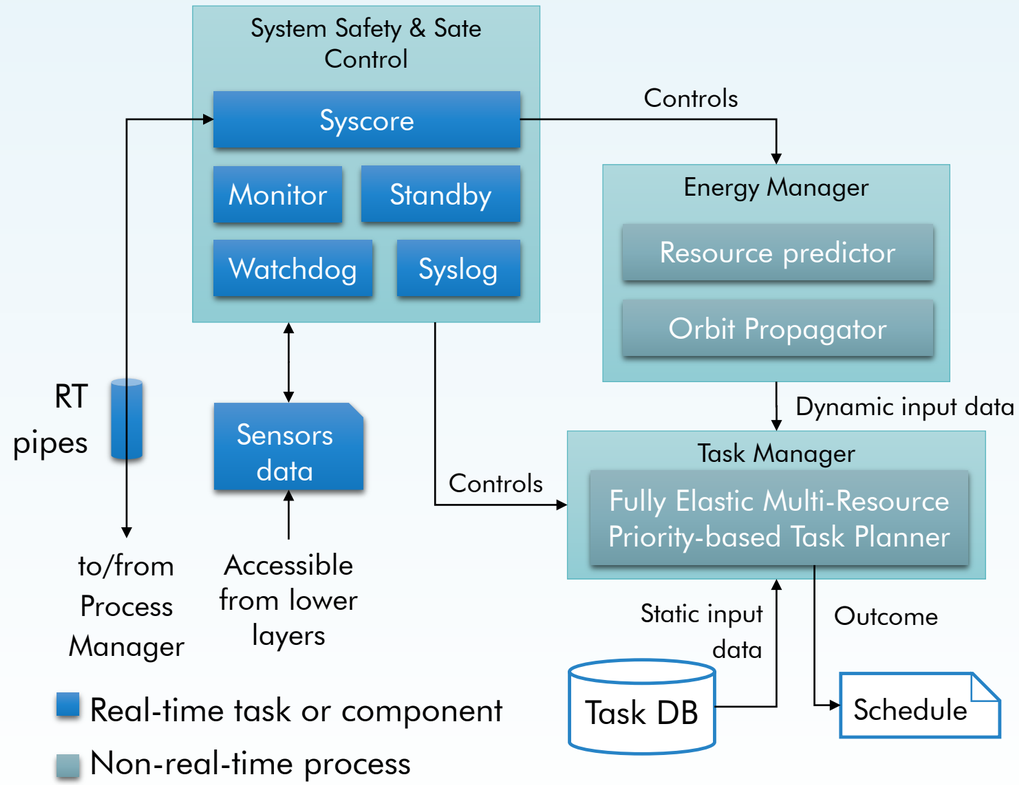


Applying design criteria: ^{3}Cat-1 software architecture

→ System Core (Syscore)

- Critical management section (RT).
- Monitors system vitals/variables: state-of-charge, temperatures, power input, latch-up's.
- Encompasses an on-board task planner.
- System State Control:

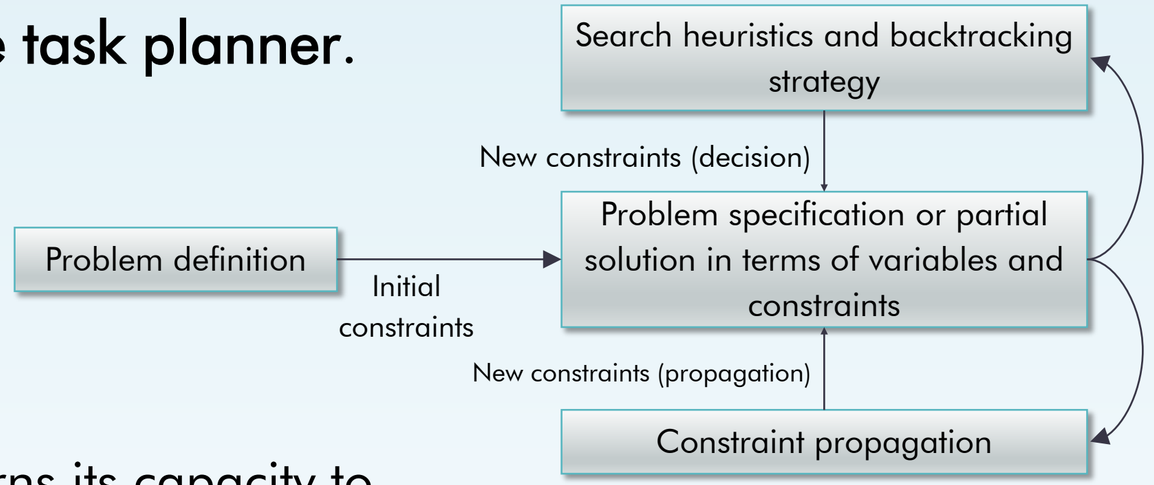


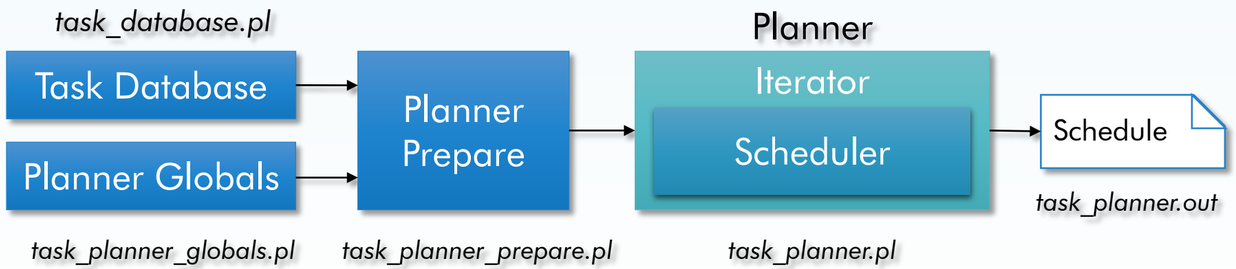


Applying design criteria: ^{3}Cat-1 software architecture

→ Autonomy System: Task Planner

- **Fully elastic, priority-based, multi-resource task planner**.
- Constraint-Satisfaction Problem solver.
- Fully-elasticity:
  - Resources capacity: dynamic.
  - Task "consumptions": variable.
- Types of dynamic resources:
  - *Instantaneous,* the removal of activities returns its capacity to the initial value (e.g. power, subsystem availability);
  - and *cumulative,* the removal of activities does not imply returning them to their initial capacity (e.g. energy, storage).





- Static constraints: environmental/mission constraints (predicted temperature, orbit position, comms. window…)
- Implemented in Prolog.

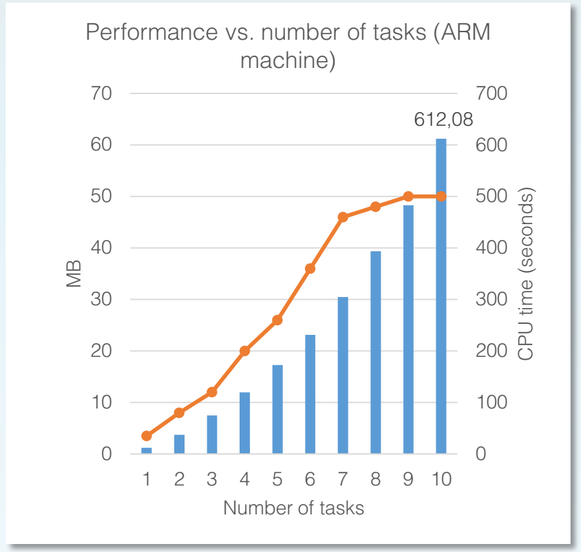
Applying design criteria: ^{3}Cat-1 software architecture

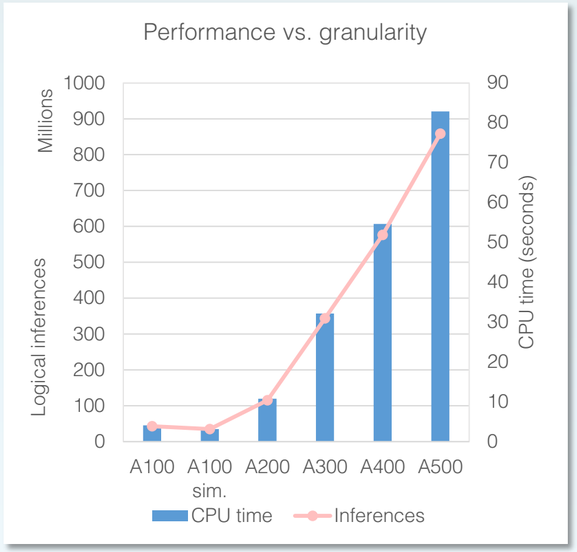
→ Prolog Task Planner open problems:

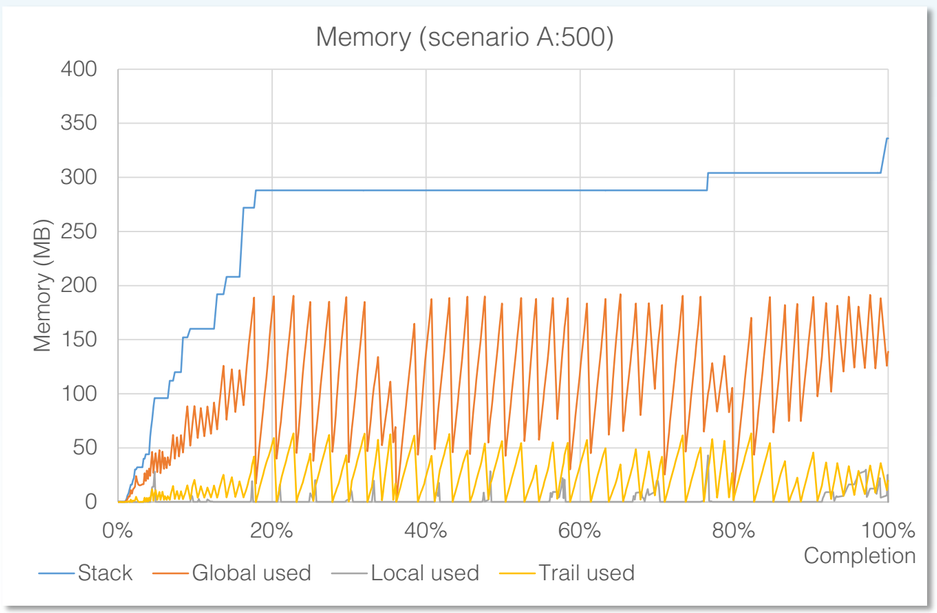
- Cumulative resource with intrinsic limits.
- Final resource capacity.
- **Performance** (CPU time and memory)

→ Affect problem complexity (worsens performance):

- Number of time units (resolution, scheduling window width)
- Number of tasks.
- Number of resources consumed by each task.
- Task consumption profiles.
- Number of cumulative resources.
- Context (inherent problem restrictions: too much constrained)







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