ATLAS

Introduction

Best Practices in integrating complex robotic systems

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KU Leuven
Febraury 2019

Outline

Practical infos

Where

KU Leuven

When

24-28 of February 2020

Who

- Gianni Borghesan (KUL)
- Diego Dall' Alba (UNIVR)
- Albert Hernansanz (UPC)

Preparation

- A PC (also VM) with Ubuntu 16 + Ros Kinetic + Orocos
- Group: General concept of the system
- Individual: **pitch presentation** a description of the module that you would integrate (behaviour, life-cycle, data exchanged) – after this presentation.

Schedule

Monday to Thursday

- Two morning sessions of 1.5 hours (9:30-11:00, 11:15 - 12:45)
- Afternoon: practical sessions & Integration (2PM - 5:30PM or later)

Friday

- Morning - Integration
- Afternoon - Evaluation (close around 4PM)
- Happy Hour

Schedule

S#	Title	Description	Who
1	Introduction	Presentation of the course, Overview of the integration process, ESR presentations,	GB, All
2	Modular integration	Modular integration, Review of modules and group definition	HA
A	ROS +Practical	ROS intro, ROS hands-on 1	DDA
3	Real Time	RT systems, Scheduling, Link to Control	GB
4	Middleware 2	OROCOS (with ROS Integration)	GB
B	Practical	OROCOS hands-on, Integration.	
5	Best practices in programming	Programming in Safety-Critical systems, revisioning.	AH

GB: Gianni Borghesan (KUL). **DDA**: Diego Dall' Alba (UNIVR), **AH**: Albert Hernansanz (UPC)

Schedule

S#	Title	Description	Who
6	Data Visualization	Data recording and display.	DDA GB
C	Practical	ROS hands-on 2, teleop. example, integration.	AH
7	Visualization	Data Visualization in medical applications, sensor registering.	DDA
8	HRI	how to convey information, haptic feedback teleop, virtual and augmented reality.	AH
D	Practical	Integration	
E	Practical	Integration	
F	Evaluation	Evaluation and Feedback	

GB: Gianni Borghesan (KUL), **DDA**: Diego Dall' Alba (UNIVR), **AH**: Albert Hernansanz (UPC)

Goal of the week

Provide the fundamental notions of:

- How to approach integration
- Software integration of complex system, consisting of:
  - Hardware interfaces,
  - (RT) control,
  - Data treatment (classification, reconstruction),
  - Decision-making systems,
  - User Interfaces.
- Tools and Libraries for robotic software development.
- Software development management.
- Real-Time and scheduling.

Outline

Scenario example - the eye surgery system

Goal

Enable the cannulation of retinal veins, and inject a drug via a $30\,\mu\mathrm{m}$ O.D. needle

Issues

- Tremor of hand
- Eye ball movement due to force on sclera
- Long infusion time (5 to 30 min)
- poor depth perception with the stereo microscope
- double puncture: injection in the retina

Eye surgery Robotic System

Scenario example - the eye surgery system

Desired features - Mechanical

- Comanipulation system
- Tremor filtering - variable damping
- (Adjustable) Remote Center of Motion
- Locking system

Scenario example - the eye surgery system

Desired features - Augmented perception

- Distance measurement retina/needle $\rightarrow$ auditory clues
- Puncture detection $\rightarrow$ auditory clues
- Vein detection $\rightarrow$ augment image.

Scenario example - the eye surgery system

Hardware components

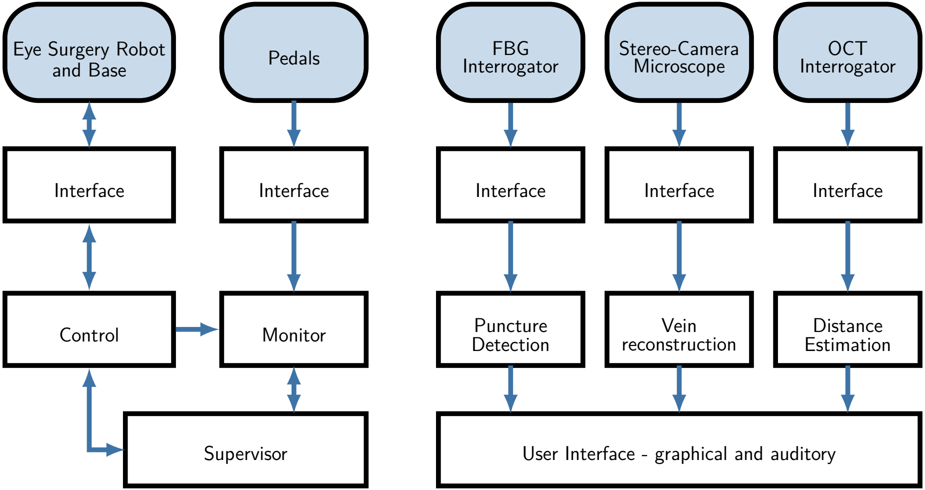
- Robot, Base for moving the RCM, Motor controllers, Pedals - on Ethercat
- Cameras on microscope with USB frame-grabber
- OCT interrogator (distance meas.)
- FBG interrogator (force meas.)
- Needle with OCT fiber and FBG integrated
- PCs

Scenario example - the eye surgery system

Software components

- Cameras interface
- OCT interface
- Robot and Pedals interface
- FBG interface
- GUI
- Auditory cues
- Image processing
- Distance estimation via OCT data.
- Robot control (different control modes)
- Puncture detection via FBG
- Supervisor(s)

Structure of the system



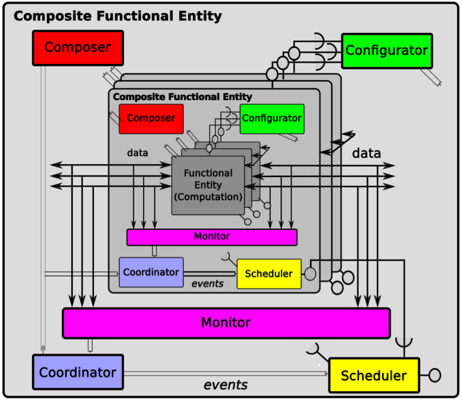
Identify the characteristics

- Which are the requirements of each part?
- Which data are required/provided, and how?
- Which are the steps to bring the system up?
- Is there a specific schedule?
- Is each system reliable? is it possible to measure?

Identify the concerns

A system can be roughly divided into 5 operations, [2]

- communication,
- computation,
- coordination,
- configuration, and
- composition.



from [10]

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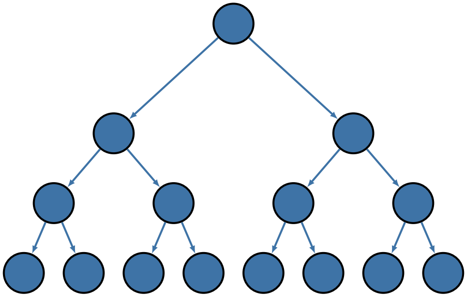
Outline

Top-Down system decomposition

The system should be decomposed iteratively in functional units

Eye Surgery system:

- Robotic system
  - robot interface
  - robot control
    - Locking (position) control
    - Tremor filtering (damping) control
  - base control
- ...



Top-Down system decomposition

Each system has one or more **functionalities**

Algorithms that compute:

- Kinematics
- Control actions
- Estimate of states of the environment
- ...

Top-Down system decomposition

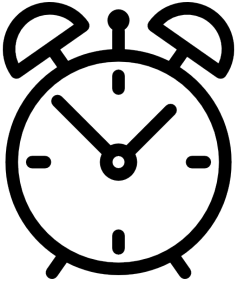
Each system/functionality has a **context** that

- Define the data that are "hidden" in the component
  - Configuration Parameters
  - States
  - ...
- Define the data that are exposed
- Define the data that are needed

Top-Down system decomposition

Each system/functionality needs to be triggered:

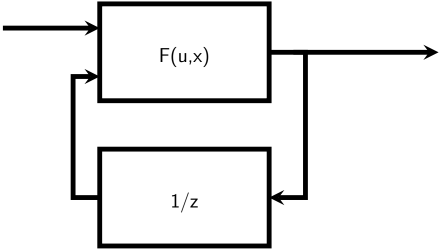
- Periodically?
- When new data arrives?
- Whenever there is time?



Example – Dynamical System

Computation

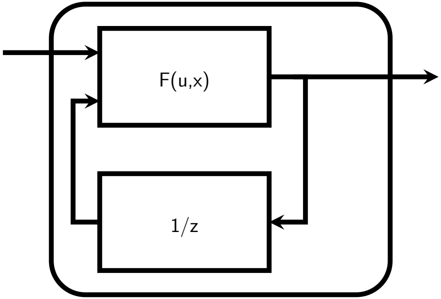
Algorithms implemented in some language.
Each algorithm is the collection and interconnection of general-purpose functionalities/libraries.



Example – Dynamical System

Context

Each algorithm needs data input and data output, plus persistent data (states). The context defines which is the boundary of these data.
Context enables modularity.



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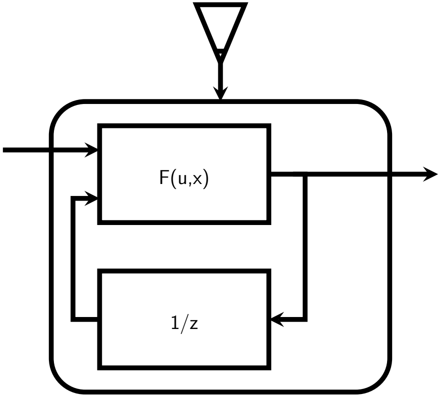
Example – Dynamical System



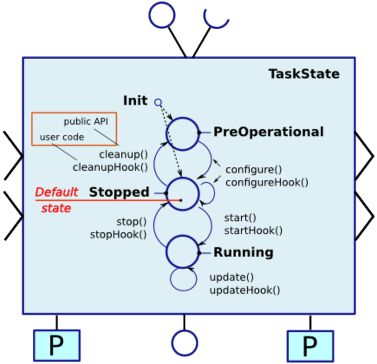
Activities

When these functions are called?

Top-Down system decomposition

Each system has (common) **Life Cycle**

- Operations that are needed to start-up.
- Different states that system should transition to.
- Conditions that trigger transitions.



Top-Down system decomposition

Each system can have a **specific Life Cycle**

Example: MaxPos Maxon ethercat motor driver:

- It has the states of each ethercat slave.
- It has its own states (in figure).

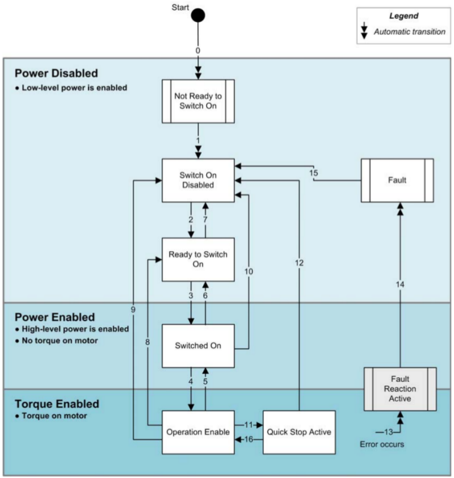


Figure 3-3 Device State Machine

Constraints of the subsystem

Each subsystem has specific requirements

- Input of data
- Timing of inputs
- State of the other components
- ...

Plan the work

Provide documentation

Rule out ambiguities

Iterate until consensus

Plan the work

Provide documentation

- interfaces
- offered capabilities
- required capabilities
- (risks)

Rule out ambiguities

Iterate until consensus

Plan the work

Provide documentation

Rule out ambiguities

- units,
- order,
- definitions,
- ...

$\rightarrow$ agree on a model.

Iterate until consensus

Plan the work

Provide documentation

Rule out ambiguities

Iterate until consensus

Verification that all the pieces works (in line of principle)

Recap - system decomposition

So far:

We agreed and documented

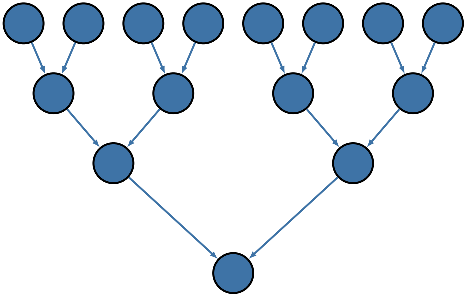
- functional decomposition in sub-systems, recursively
- breakdown of life cycles
- breakdown of requirements and capabilities

Bottom-Up system composition

To do

for each level we:

- Implement (following the specification)
  - Connect ?
  - Synchronise ?
- Verify (vs. specification) possibly with unit testing



One step back to the 5Cs (before implementation)

Communication

- Frequency ?
- Real time ?
- Size/Buffer ?

Coordination

- Synchronize
- Scheduling

Configuration

- Offline
- Online

Computation

- Real time?

Composition

One step back to the 5Cs (before implementation)

Communication

- Frequency ?
- Real time ?
- Size/Buffer ?

Coordination

- Synchronize
- Scheduling

Configuration

- Offline
- Online

Computation

- Real time?

Composition

Some operations that are common to all the subsystems

Re-use of same libraries/infrastructure!

Introspection

Introspection is the ability of a (sub-)system to make explicit its state.

- the life cycle is the first approximation
- Systems may have more complex/nested state $\rightarrow$ **Explicit Modelling**
- Systems should make aware other systems of their state for
  - logging and
  - feedback on coordination, fault recovery.

Monitoring

Monitors can evaluate:

- The state of world - from continuous domain to symbolic information
- The state of systems
  - watch-dog
  - compare output with expected output

Choice of tool(s)

Depending by the characteristics of each of the **5C**, each part of the subsystem can rely on different tools, mainly offered by:

- Language
- Library

Choice of tool(s)

Language

- Low-level, strongly-typed languages offers deterministic performances.
- Scripting languages are normally good for deployment (e.g. Lua) or non-realtime tasks (e.g. Python).
- Some languages are better supported by libraries (e.g. Python) or for specific tasks.

Choice of tool(s)

Libraries - computation

Stand-alone libraries (that depends also by language) Some examples:

- Kinematics: KDL, expressionGraph, ...
- Math/Albegra: Eigen, LAPACK, numpy, ...
- Visualization: Qt, pyside, pyqtgraph, ...
- Optmization: qpOASES, Casadi, ...

Important!

Choose wisely, because these are strong dependencies...

Choice of tool(s)

Libraries - communication, synchronisation, configuration, deployment.

This is typically a layer offered by a middle-ware. Some examples:

- ROS, ROS 2 [9]
- Orocos [1]
- Yarp [3]
- Miro [8]
- Taste [6, 7]
- MicroBLX [4]

Inter-process communication middle-ware that can be applied to robotics:

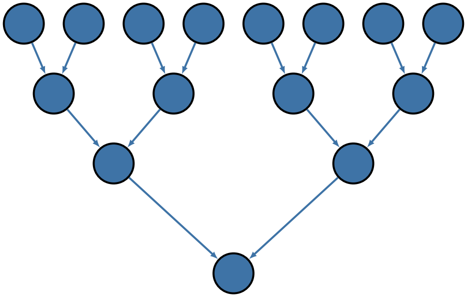
- ZeroMQ,
- Corba

Refer to [5] for more example.

Implementation

Algorithm

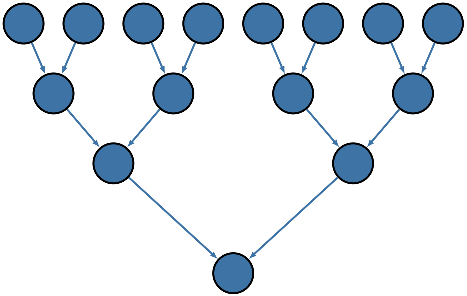
- **Independent** – no unnecessary dependencies with e.g. the middle-ware
- **Isolated** – It does a single thing, limit side effects
- **Testable** – make unit tests, if possible.
- **Documented** !



Implementation

Composition of Algorithms

- Does the algorithm has a life cycle ?
- Is it shared with others ?
- Data flow follows a strict causality ?
- Coordination ?



Division (or not) into activities and contexts !

Implementation

Composition of Algorithms – Example

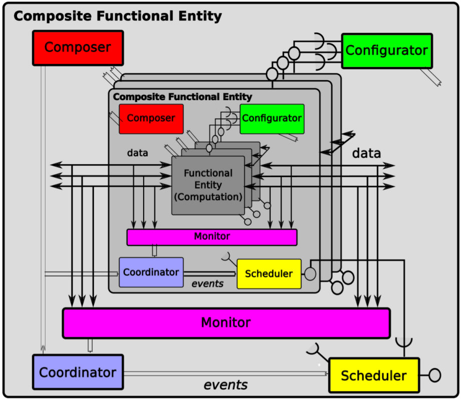
1. HW interface of robot – data in
2. Forward kinematics
3. Control action in user (Cartesian) space
4. Inverse/Transpose Differential kinematics
5. Control action in joint space
6. Safety control
7. HW interface of robot – data out

Implementation

Composition of Algorithms – Result

From outside, is a system with

- a functionality
- a life cycle
- a data flow
- a “behavioural” interface
- a trigger
- a configuration interface



from [10]

Composition of systems

Systems can be deployed

- in the same process
- in the same machine (IPC will be needed)
- in different machines

Issues of composition: communication and coordination

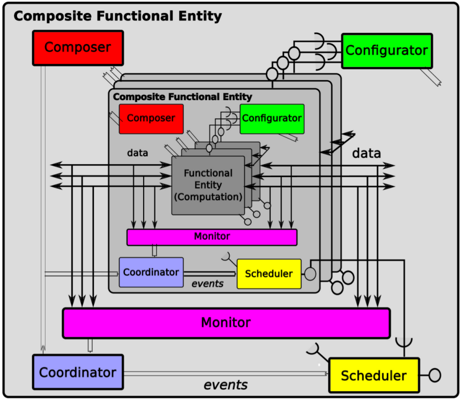
- Data sharing mechanism: latency, bandwidth, jitter, RT
- Explicit scheduling
- Additional coordination

Composition of systems

Implementation – Ideally

From outside, is a system with

- a functionality - given by other system
- a life cycle
- a data flow
- a “behavioural” interface
- a trigger
- a configuration interface



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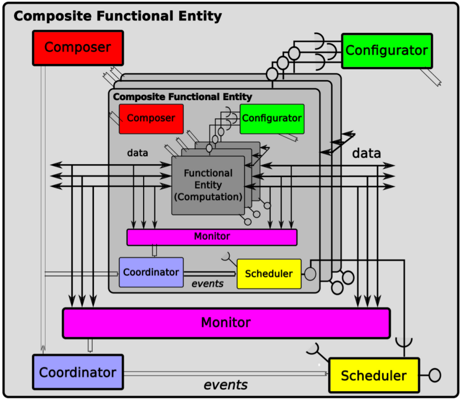
Composition of systems

Implementation – In reality

Some aspects lack support for scaling

- behaviour are integrated
- communication is flat
- synchronization is flat
- introspection tooling is very limited
- ...



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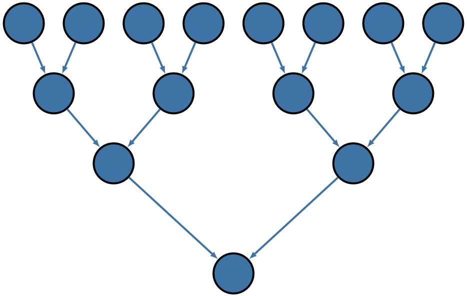
Verification

After each composition

- Verify (vs. specification) possibly with unit testing
- Document

if verification fails:

- Correct, or
- Relax specification, if possible.



Questions ?

Groups

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