Advanced Control Techniques For Dynamic Testing of Wind-turbine Drivetrains

Javier Ariño. → jarino@idom.com

17,18 September 2014, Charleston

Outline of the presentation

Advanced Control Techniques

for Testing Wind-Turbine Drivetrains

Outline:

- AEC-Idom Presentation
- Test Facilities Overall Requirements
- Control Systems: Architecture and Requirements
- Advanced Control Techniques: strategies
- Example: DyNaLab Non Torque Load Application System

Idom presentation

IDOM is an independent firm of Engineering, Architecture and Consultancy services that operates globally in areas such as power generation, oil & gas, renewable and alternative energies, manufacturing industry, civil infrastructures, nuclear plants, large technological and scientific facilities, architecture and unique challenging structural projects.

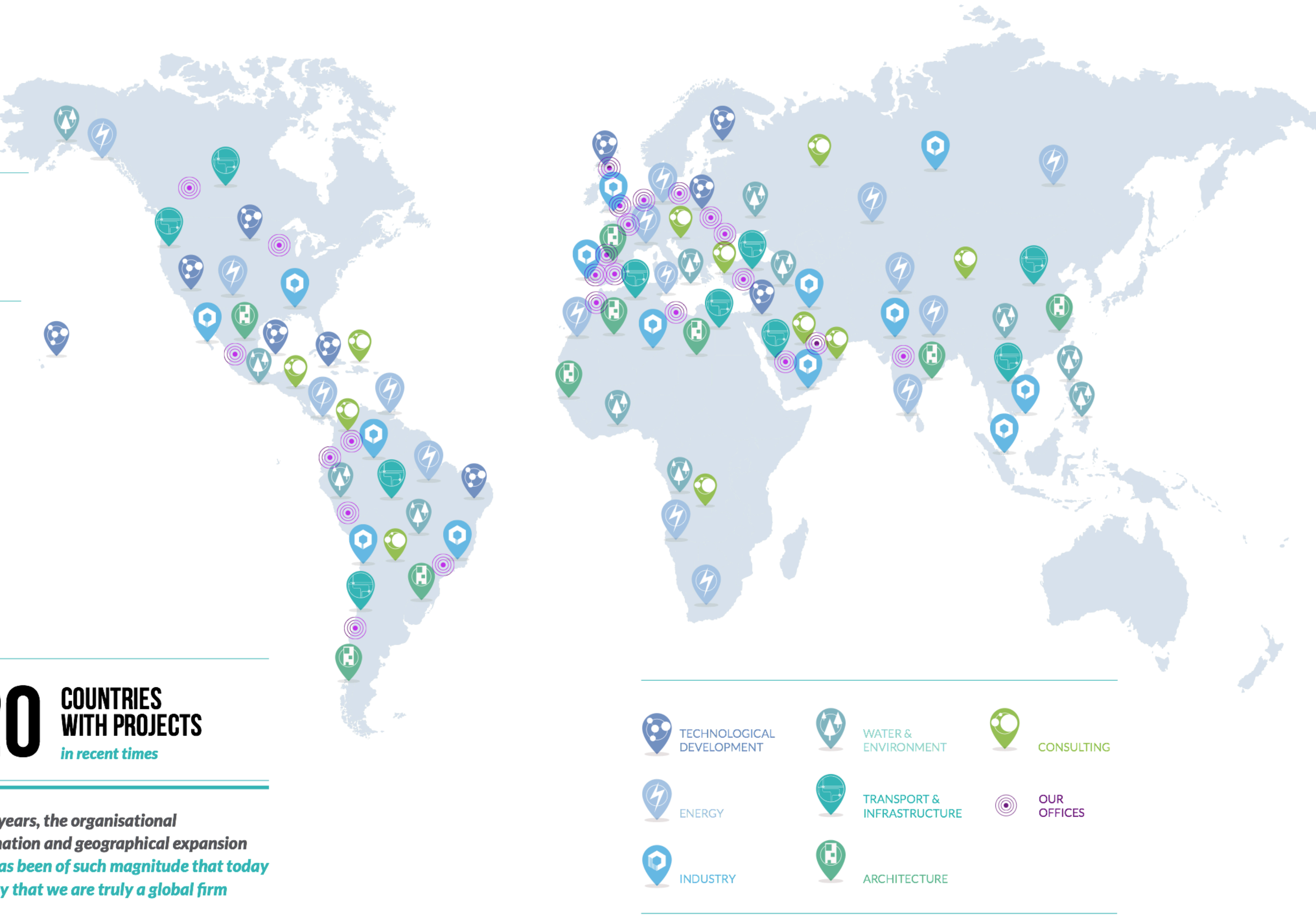
IDOM Headquarters in Bilbao

A few facts about IDOM

- Founded in 1957
- More than 2.500 professionals in 20 countries, 37 offices and 4 continents
- 200 M€ in professional services in 2013
- 100% owned by employees. 23% of the employees are partners.
- IDOM philosophy is based on:
  - Service focused on the client
  - Realistic, efficient and multidisciplinary team
  - Improvement faced with new challenges
- Giving solutions to more than 5.000 clients in 40 countries and performing more than 15.000 projects

Some Projects
2011 / 2013

37
OFFICES IN
20
COUNTRIES



120 COUNTRIES WITH PROJECTS
in recent times

In recent years, the organisational transformation and geographical expansion of Idom has been of such magnitude that today we can say that we are truly a global firm

Activity areas of the company:

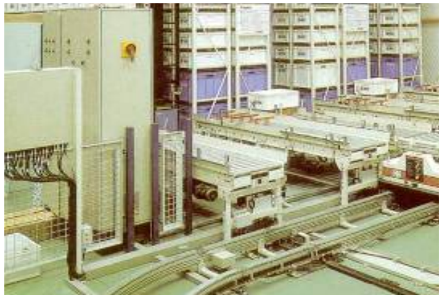
Architecture

- ACXT Architecture
- Structural Engineering
- Installations Engineering
- Project Management

Industry & Energy

- Power generation plants: fossil, renewable, etc.
- Electricity transmission and distribution facilities
- Industrial plants, in every sector
- Natural gas, refining, petrochemical
- Environmental assessments, waste consulting
- Engineering for science, telescopes, moveable domes, research facilities

Consulting



- Industrial restructuring
- Sectional studies and planning
- Competitive strategy
- Diversification strategies and internationalization
- Business plans
- Logistics and operations

Civil Engineering

- Roads
- Railway works, high-speed and light rail
- Foundations and Structures
- Hydraulics and sanitary engineering

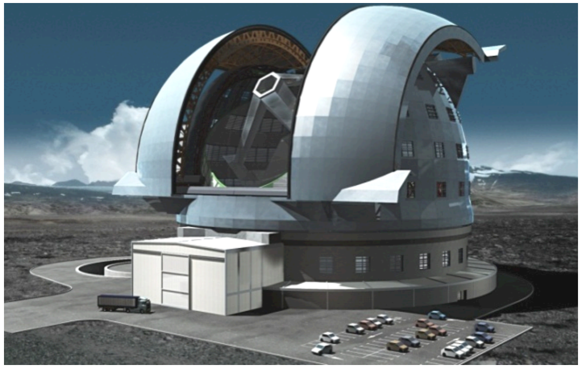
Idom ADA

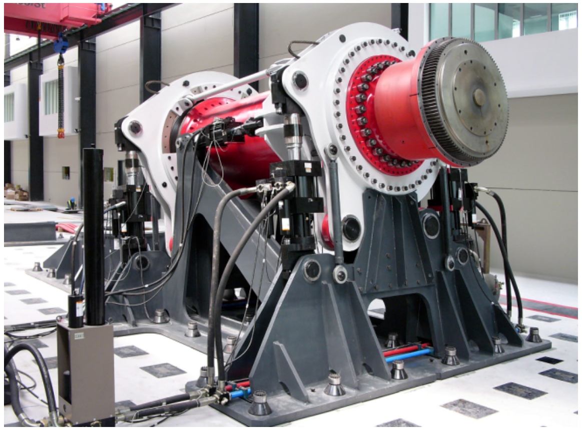
IDOM Advanced Design & Analysis (ADA)

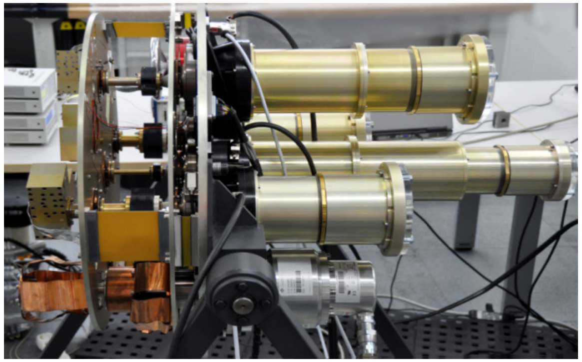
Department is an IDOM technical department whose mission is to develop non-conventional engineering projects. Typical IDOM ADA projects involve engineering for science, technological installations, product design, special mechanism and machine design, non-conventional structures and numerical simulation.

IDOM ADA work team offers,

- Broad expertise in applied mechanics, structural design , electronics and control
- Sound project management skills to deal with large, complex and multidisciplinary projects
- Intensive use of advanced computer simulation and in-house prototyping & testing techniques







Idom ADA

Wind-Turbine Testing Facilities Background

In the last years, IDOM ADA has directly been involved in projects related to **<u>Large Drive Train Test Facilities</u>**, in particular:

- **CENER Wind Turbine Test Laboratory:**

Full design and construction management, including four test rigs (drivetrain, generator, full nacelle, and assembly stand) and the facility including the facility building and auxiliary installations.

- **Clemson University Restoration Institute Drive Train Test Facility:**

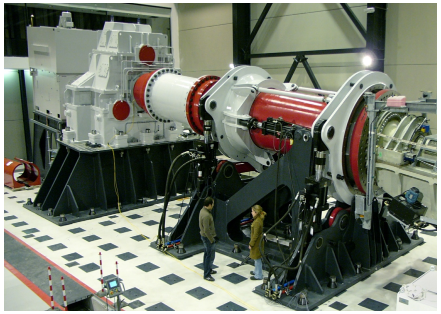
Complete design of the facility, test rig foundations , integration services and assistance to construction.

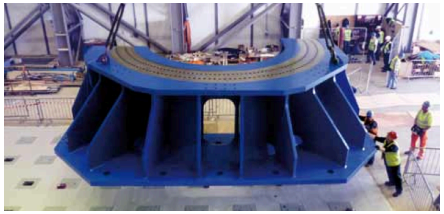
- **NAREC Fujin Drive Train Test Facility:**

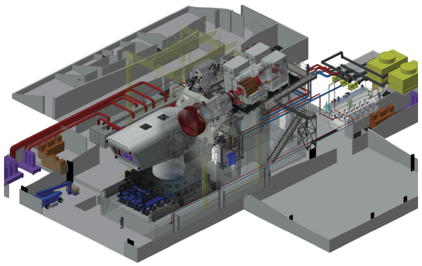
Detail design for construction of the strong-floor foundation and machine supports.

- **Fraunhofer DyNaLab Testing Facility:**

Design and construction management the contract to design of the facility building and auxiliary installations. Turn key supply of the 10 MW test bench.

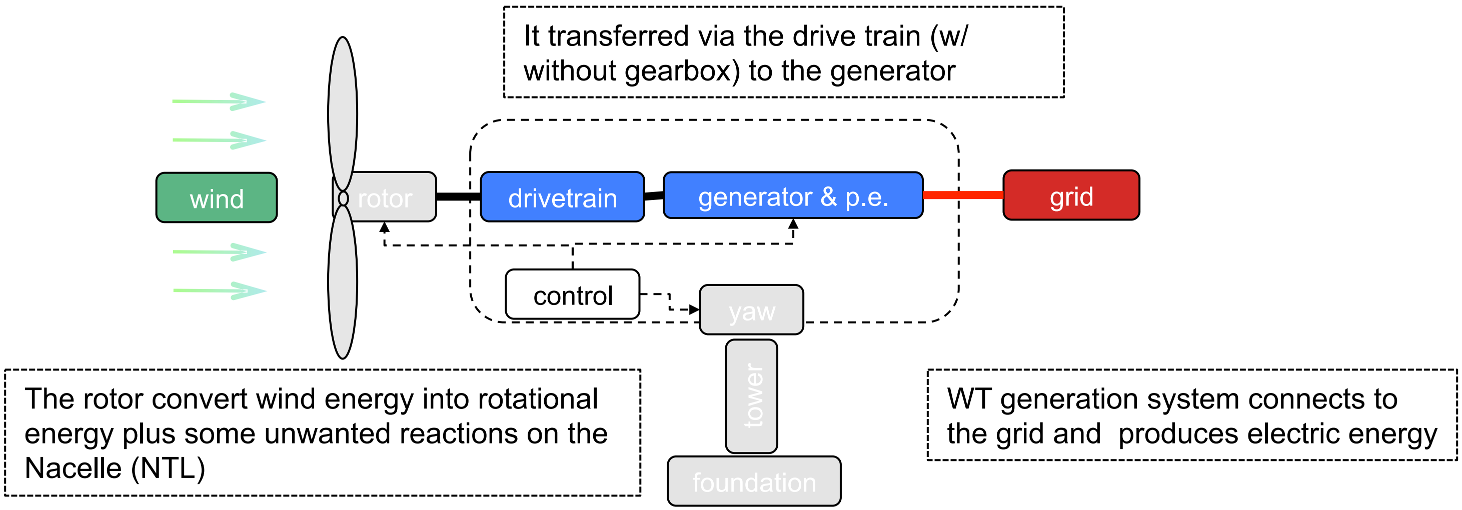






Test Facilities Requirements

General Overview, systems involved.



Main functional capabilities:

- Provide-simulate the power input → rotational torque and non torque loads
- Provide-simulate the power output → controlled voltage/frequency sinking source

Additionally :

- Command the DUT
- Data acquisition and recording. (>1000 sensors)
- Supervision of test facility auxiliary system: electrical system, cooling, hydraulic,...
- SAFETY!

Testing Facilities Functional Requirements

Provide Torque and Non torque Loads under different use cases:

- Performance test.- idling, generation, start, run and stop cases, standard zones I to IV.
- Design Verification & Validation tests. Different load cases , future certification?
- Off-normal tests.- emergency stops, overload (including static), over speed, etc.
- Endurance → HALT, highly accelerated lifetime testing
- R&D tests → prototypes set-up, control system development

Provide a Power Grid Connection under different use cases:

- Performance test.- Active power control, Reactive power control, QoE measurement, etc.
- Design Verification & Validation .- Certification under a wide range of grid conditions for compliance with different grid codes and standards, grip operators.
- Off-normal tests.- LVRT, ZVRT, frequency events, phase unbalance, etc.
- R&D tests → prototypes set-up, control system development , etc.

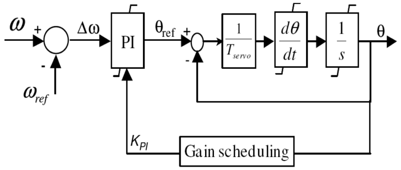
Testing Facilities Functional Requirements

HIL integration is necessary due to some main reasons:

- Simulation of missing systems: rotor, pitch system, tower, yaw system.
- Simulation specific location: variations in wind conditions, grid conditions, foundations.
- R&D testing: WT control system development

Some HIL possibilities:

- Aerolastic simulation, torque AND NTL generation with wind series.
- Rotor simulation: Inertia, pitch control system.
- Tower and Yaw system simulation.
- Grid conditions simulation. Strong, weak grids, specific location modeling,..



Some HIL use cases:

- Torque damping techniques, model based torque controllers, filtering, pitch control,…
- NT loads: pitch control, passive yaw slip, generator power tracking point ..)
- Grid events: Wind Power Plant simulation, off-normal cases,…

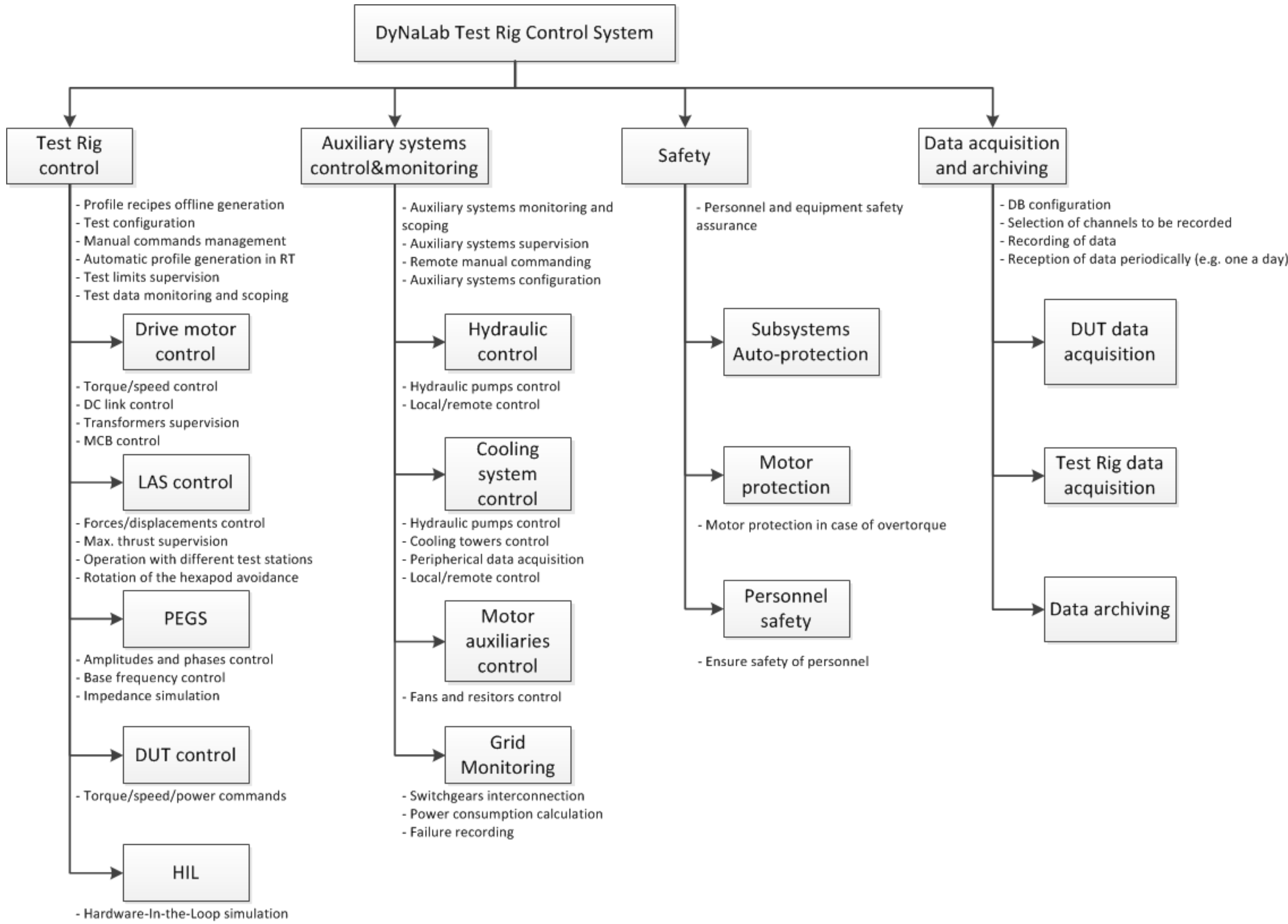
General Overview: DyNaLab

- **Test Rig Control:** control of the four main mechanical and/or electrical subsystems that in combination provides all the moments, forces and electrical grid conditions to which a Nacelle is subjected in real environment

- **Aux. systems control & monitoring:** control the auxiliary installations that serves the previous main subsystems

- **Safety:** ensure the safety of personnel and equipment

- **DAS & data archiving:** DUT and test rig relevant data acquisition and recording



Modern test bench requirements

Test Benches Requirements / Inputs:

- ✓ Control on hard Real Time. Coordination of different subsystems.
- ✓ Power Inputs → accuracy, dynamic issues
- ✓ HIL integration capabilities: rotor, pitch, yaw, grid,..
- ✓ DAQ synchronization and mass storage.
- ✓ Safety: personnel and equipment safety. E-stop coordination.

Test Benches Requirements / Outputs (grid connection requirements):

- ✓ LVRT as per different grid codes
- ✓ Voltage and frequency variations, flickers
- ✓ Simulation of Power Plant Grid
- ✓ Stability, low Harmonics
- ✓ Short circuit capability

Control System Requirements

DyNaLab Test Rig Main Control

TRMC

- Configuration, programming and control of the tests.
- Remote commanding and monitoring of the test rig as a whole
- Coordination of the test rig subsystems in mili-second range

DRIVE MOTOR CONTROLLER

LASC

LSS INSTRUM.

DUT CONTROL

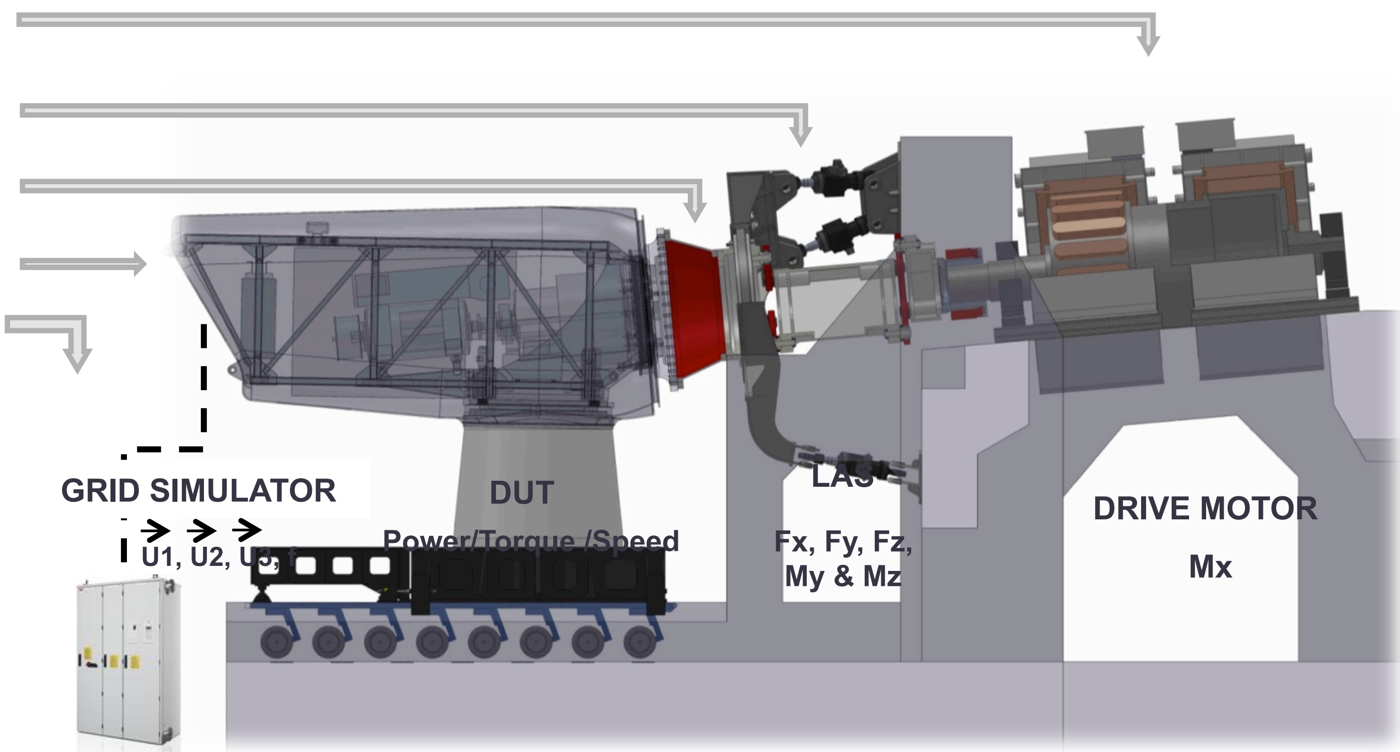
PEGS

HIL

SAFETY

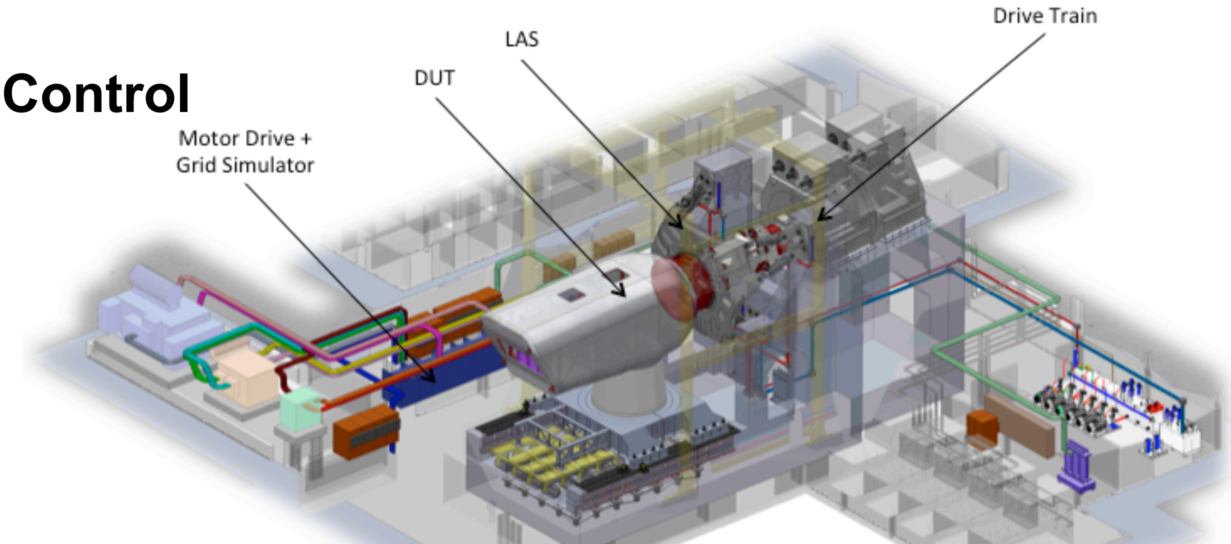
DATABASE SERVER

SCADA



Control System Architecture

DyNaLab Test Rig Control



- Fieldbus interfaces (EtherCAT)
- Cabled signal interfaces

HIL → **Test Rig Main Controller**

- Test Bench Configuration
- Profiles and procedures generation
- Test Control: Automatic, manual
- Test Monitoring & Scoping

Drive Control

- Drive Control: torque, speed, position
- Load sharing
- Active rectifier control
- Main circuit breaker control
- DC bar control
- INU protection
- Motor protection
- Transformer protection

LAS Control

- 6 x lineal axis control: force, displacement, open loop
- 6 x 1 axis safety
- 6 x 1 axis parameterization
- Max thrust control
- Fieldbus/safety interfaces

Grid Simulator Control

- Grid Control: U_A, U_B, U_C and associated angles
- Base frequency control
- Impedance simulation
- INU protection
- Fieldbus/cabled signal interfaces
- Fieldbus/safety interfaces

DUT

- Fieldbus interfaces (generic Ethernet I/F)
- Safety interface

Advances Control Techniques

Why advance control systems are needed

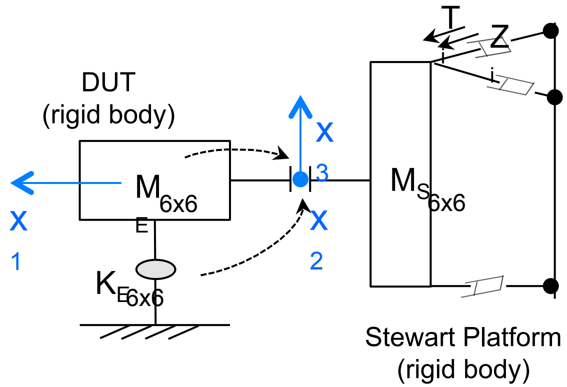
- Ever-increasing requirements in power, performance, and sophistication
- Strict requirements of control accuracy →certification related.
- HIL integration issues → aerolastic models, pitch models, grid models, etc…
- Testing for DUT control research: → new control techniques
- Exponential growth of wind turbine size → Dynamic Issues even in the test bench!!!

DyNaLab example, what are we doing?

- Real-Time overall control systems, synchronizing all systems (10 mS)
- Model based active damping for drive control.
- Advance firing pulse pattern techniques for grid simulator, 0 to 120% V, THD < 2%
- HIL integrated, direct I/F to the overall controller, and fast I/F to Grid simulator and torque control (μs range)
- Advance model based controller for Load Application System.

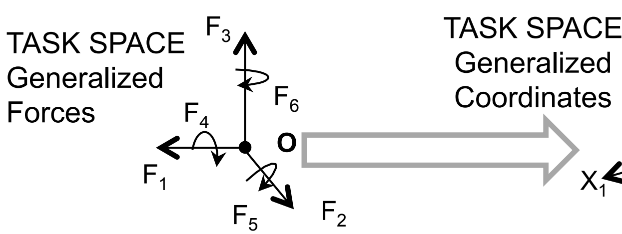
LAS SYSTEM DESCRIPTION

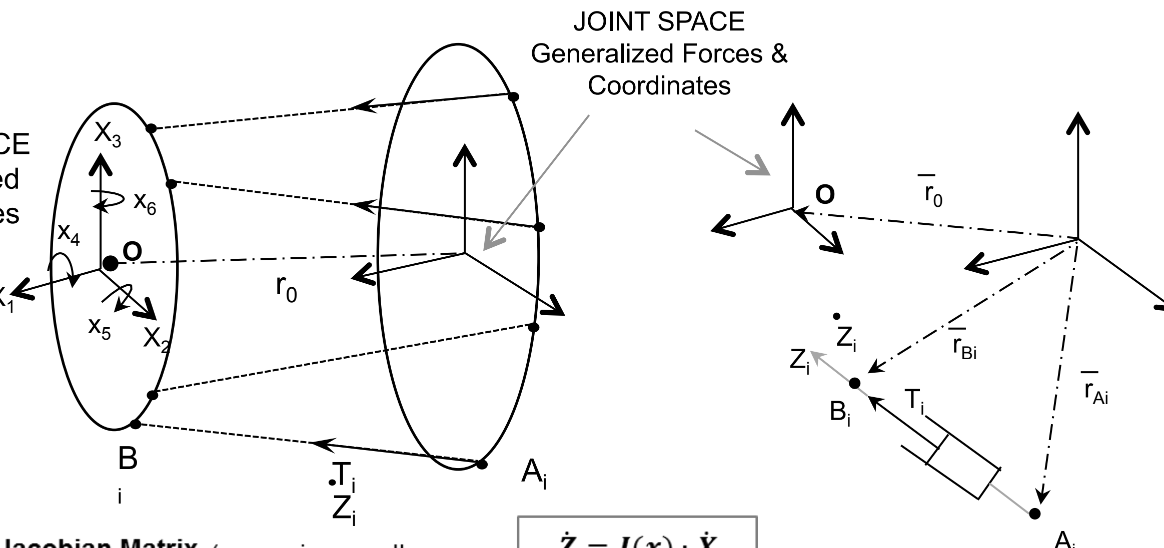
System Representation



	Displacements	Forces
TASK SPACE	$X = (x_1, x_2, \ldots x_6)^T$	$F = (f_1, f_2, \ldots f_6)^T$
JOINT SPACE	$Z = (z_1, z_2, \ldots z_6)^T$ 6 actuators	$T = (T_1, T_2, \ldots T_6)^T$

Stewart Platform Kinematics





- Inverse kinematics is explicit: $\boldsymbol{Z_i = Z_i(X_j)}$

$$\partial Z = \begin{Bmatrix} \partial z_1 \\ .. \\ \partial z_6 \end{Bmatrix} = \begin{bmatrix} \frac{\partial z_1}{\partial x_1} & \cdots & \frac{\partial z_1}{\partial x_6} \\ \vdots & \ddots & \vdots \\ \frac{\partial z_6}{\partial x_1} & \cdots & \frac{\partial z_6}{\partial x_6} \end{bmatrix} \cdot \begin{Bmatrix} \partial x_1 \\ .. \\ \partial x_6 \end{Bmatrix}$$

Jacobian Matrix (assuming small displacements)

$$\boldsymbol{J(x)} = \left[\frac{\partial z_i}{\partial x_j}\right]_{i,j}$$

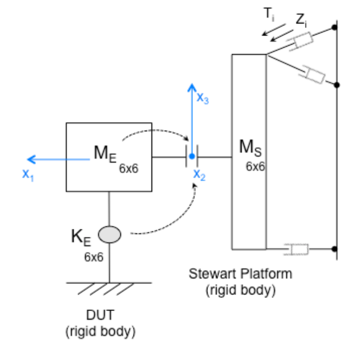
i = 1…6
j = 1…6

$$\boxed{\dot{\boldsymbol{Z}} = \boldsymbol{J}(\boldsymbol{x}) \cdot \dot{\boldsymbol{X}}}$$

$$\boxed{\boldsymbol{F} = [\boldsymbol{J}(\boldsymbol{x})]^{T} \cdot \boldsymbol{T}}$$

SYSTEM DESCRIPTION

System Dynamics – LAS block diagram



$$F = J^T T$$

$$F = (M_E + M_S)\ddot{X} + \cancelto{0}{V(X,\dot{X})} + \cancelto{G}{G(X)} + K_E X + F_{Di}$$

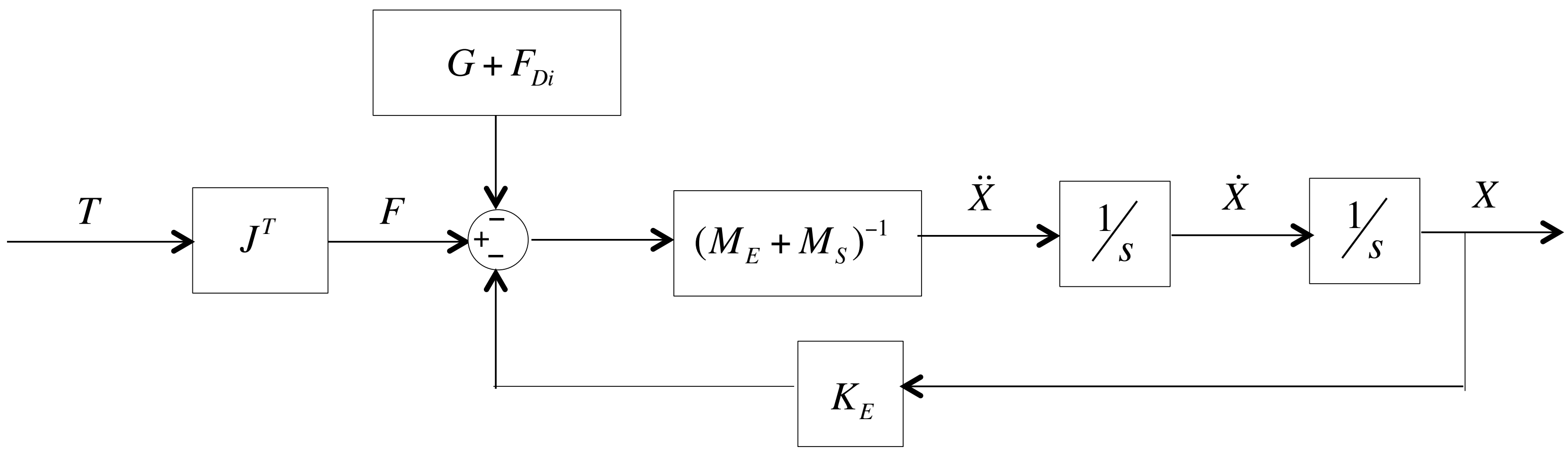
$$J^T T = (M_E + M_S)\ddot{X} + K_E X + G + F_{Di}$$

M_E, M_S, K_E: referred to the end-effector

$G \approx$ constant in the case of small displacements

F_{Di}: disturbance forces due to the coupling

G, F_{Di}, model computable disturbances

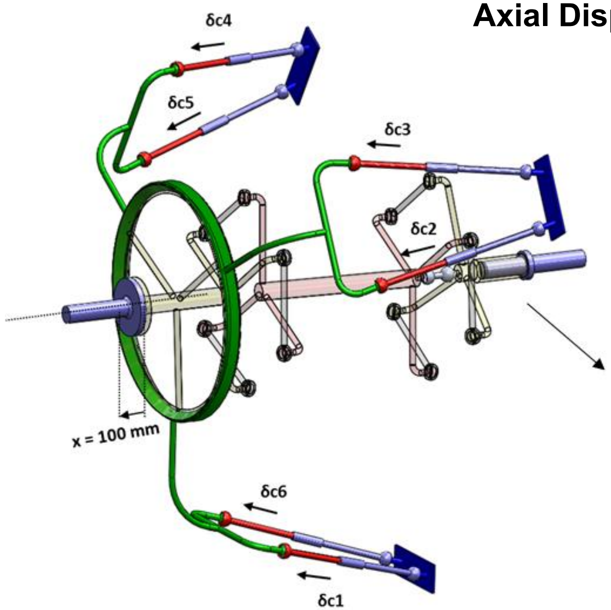


LAS SYSTEM DESCRIPTION

Stewart Platform Kinematics

Evaluation of non-linearity effects and accuracy of the linear approximation applied when considering the Jacobian matrix as the system transformation matrix.

Axial Displacement X_1



Input: x= 100 mm

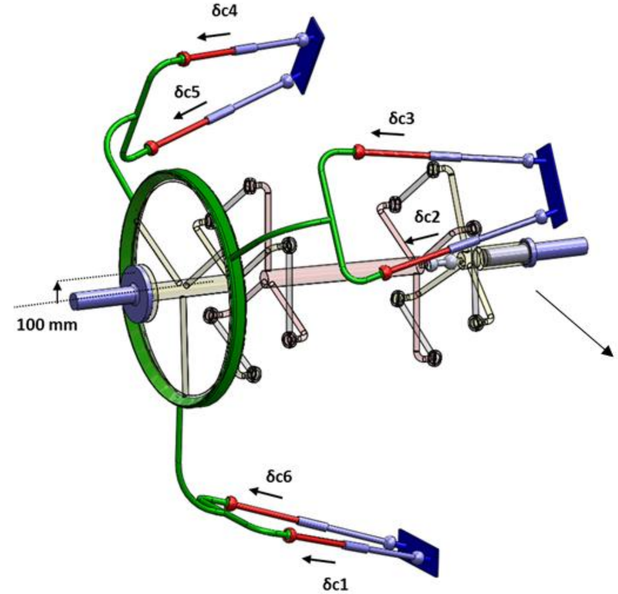
Resulting Displacements on Cylinders (non-linear):

$$\begin{Bmatrix}\delta_{c1}\\ \delta_{c2}\\ \delta_{c3}\\ \delta_{c4}\\ \delta_{c5}\\ \delta_{c6}\end{Bmatrix} = \begin{Bmatrix}94.84\\ 94.84\\ 94.84\\ 94.84\\ 94.84\\ 94.84\end{Bmatrix} \text{[mm]}$$

Inverse transformation when using Jacobian matrix:

$\{\delta xj\}^T=\{\underline{100.18}\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\}$ ⟶ error = 0.18 %

Radial Displacement X_3



Input: z= 100 mm

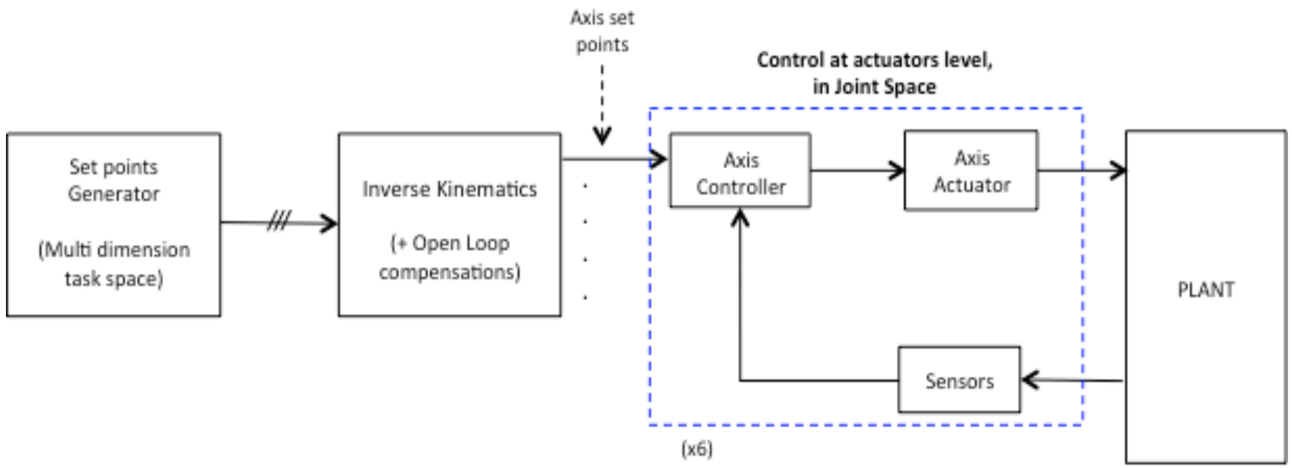
Resulting Displacements on Cylinders (non-linear):

$$\begin{Bmatrix}\delta_{c1}\\ \delta_{c2}\\ \delta_{c3}\\ \delta_{c4}\\ \delta_{c5}\\ \delta_{c6}\end{Bmatrix} = \begin{Bmatrix}27.22\\ -28.15\\ 5.67\\ 5.67\\ -28.15\\ 27.22\end{Bmatrix} \text{[mm]}$$

Inverse transformation when using Jacobian matrix:

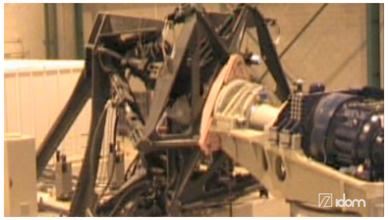
$\{\delta xj\}^T=\{1.67\ \ 0\ \ \underline{100.20}\ \ 0\ \ 0.02\ \ 0\}$ ⟶ error = 0.2 %

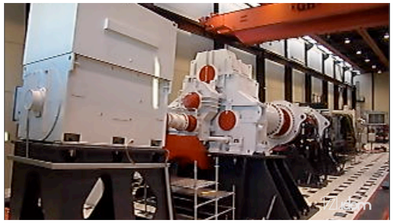
Standard versus Advanced control techniques



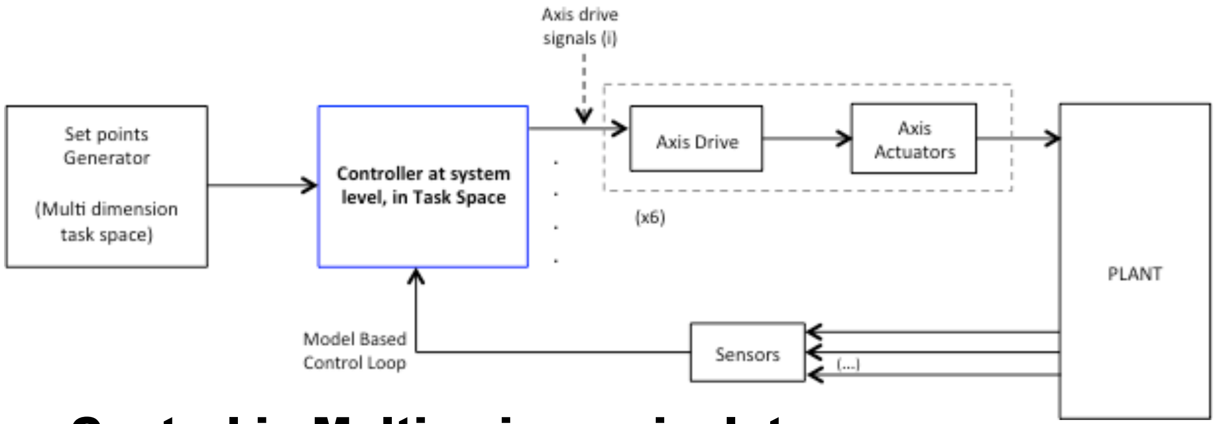
Standards Control in Multi-axis manipulators:

- Action on DUT → transformed in force/displacement commands in actuators in open loop scheme.
- Open loop scheme and can be simple or sophisticated –e.g. can include computation of inertial forces, gravity forces, static deformations and others.
- Command closed at actuator controller independently with PID techniques.





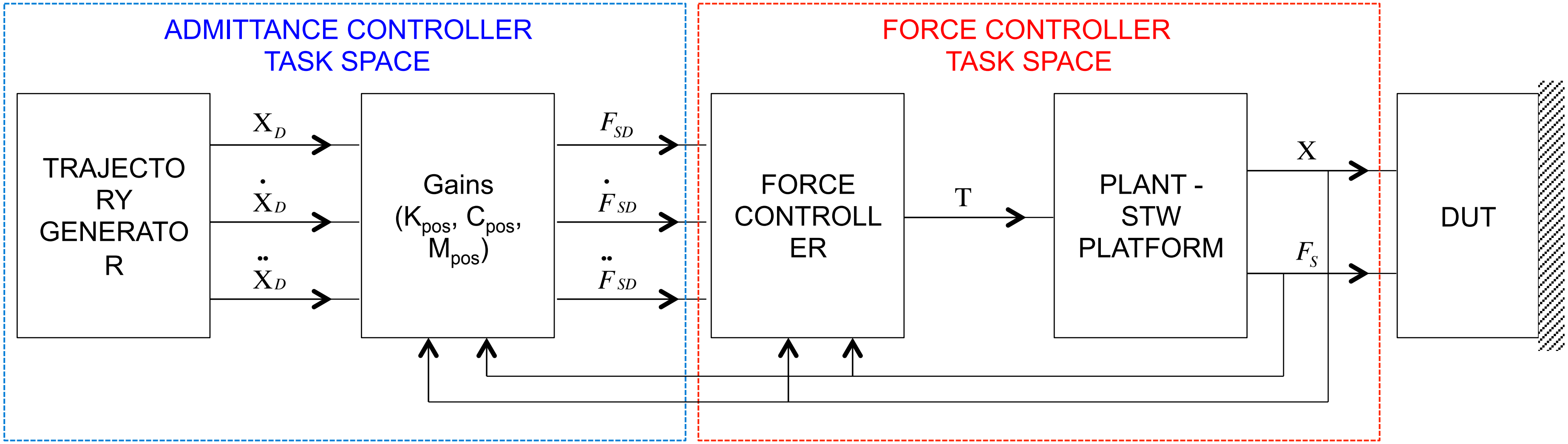
Standard versus Advanced control techniques



Advance Control in Multi-axis manipulators:

- Control loops are closed in the task space and not in the joint space.
- Model-based systems that make use of plant dynamics knowledge in order to better determine the actions required from the several actuators (axes or joints).
- Single unified approach, model-based Explicit force controller on top of a displacement control loop (Impedance/Admittance based) to control the manipulator, applicable to all use cases:
  - ✓ free motions → (test set-up)
  - ✓ kinematically constrained motions (contact, clashes when docking, undocking)
  - ✓ dynamic interaction between the manipulator and the DUT. (testing)

Model Based Advanced Control System



Force Controller

- I/F force (Fs) to be controlled with feedback and feedforward, using Control Law Partitioning techniques; i.e. model based computed force algorithm, loop developed in Task Space

Admittance Controller

- For position control during platform maneuvering
- For x_4=0 (ϕ=0) control during tests on the DUT

Impedance/Admittance Position Controller

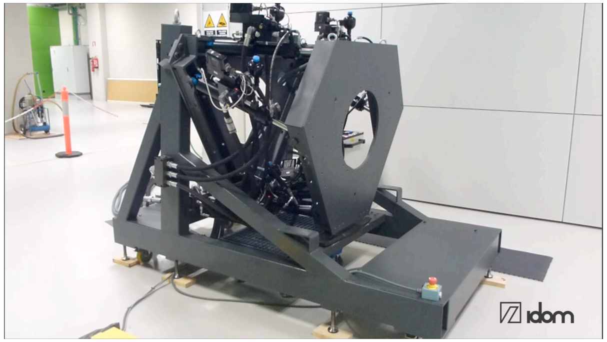
- Impedance controller built over the Explicit Force loop described in the previous section is proposed for position or hybrid force/position control modes.
- Based in modern position control strategies for manipulators where interferences with complex surrounding environments (DUT) has to be avoided or kept controlled.
- Defined through lineal virtual potential fields: i.e. defining a 6 d.o.f. spring between the real position and the desired one.
- This linear scheme can be upgraded by adding a virtual mass and/or, more conveniently, a virtual damping for smooth platform displacements.

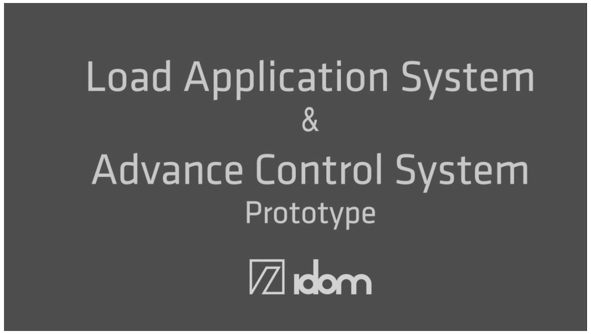
Briefly said, the position controller sends the explicit force controller a command that is computed based on the difference between the position set-point and the actual position value.

Development Approach:

The works are divided in 3 main phases

- Design Engineering:
  - ✓ analysis of system dynamics and system modelization.
  - ✓ design of advanced control loops.
  - ✓ simulations for a preliminary validation of the proposed controllers.
- Prototyping and Validation tests:
  - ✓ on scaled physical setups
  - ✓ different systems under study
- Implementation on DyNaLaB during 2015





Thank You

Questions?

You can refer any further question to → Javier Ariño jarino@idom.com

For more information visit → www.idom.com/ada