Industrial robot simulation models for control design and analysis purposes

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Abstract

"Simulation" is a word covering many design and analysis tools used in industrial design processes. A class of simulation models for "realistic" industrial robot simulation will be presented. It is intended as a tool for the development and the design of industrial robot automatic control systems. We will discuss the physical meaning of this class of models, and the reliability of the simulation results against real robot behavior. We introduce some simple concept and tool to verify if the simulation model could be accepted as a "virtual robot prototype". During the ACODUASIS project, the simulation model was implemented in EICASLAB as a system "fine" model to design and verify independent motor position servo controllers.

Keywords: "fine" model development for servo control design purposes, not rigid robot modeling, robots with elastic joints, robot model identification, realistic robot simulation.

1 Introduction

Automatic control system analysis, design and assessment is our purpose for realistic robot modeling and simulation. The first part of the work is devoted to introduce a "simple" model for not rigid robot: the elastic joints (EJ) robot model. We will discuss the reasons for introducing some approximation and assumptions. With some field results, we will see that the EJ modeling is still good enough for industrial robots. The EJ model is object oriented and in the second part of the work we will show some simulation results and will compare them against real behavior.

2 Not rigid robots and model complexity

The model proposed represents a not rigid machine, typical feature of industrial robots and key factor to understand robot application state of art. Taking the joint motor current I_{mi} as input variable, the plant shows anti resonance/resonance behaviour on motor velocity $\dot{\theta}_{mi}$ (see **Fig.6** as a typical experimental frequency plot) and pure resonance on link (joint) velocity $\dot{q}_i$. These resonances brings in vibrations (complex poles) with very low dumping factor and frequency that changes with load condition (inertia). These resonance frequencies are usually lower than *20 Hz* (for high load conditions can be lower than *5…10 Hz*). This gives "bandwidth" and performance limitations. The dynamic model must be accurate in the frequency range from 0 to 100 Hz. This fact defines the detail and the complexity level of the simulation model.

2.1 Why elastic joint (EJ) modeling for industrial robots

In industrial robots the elasticity effects are introduced by three main causes:

- the presence of transmission elements such as:
  - gearboxes and transmission belts,
  - long shafts (e.g., last 3-dofs of many industrial robots),

  introduce elasticity effects between actuating inputs and driven outputs.
- Distributed link deformation always introduce elasticity effects: 'link rigidity' is always an ideal assumption and may fail when increasing payload-to-weight ratio, motion speed, control bandwidth.
- The presence of parasitic degrees of freedom, due to non ideal behaviour of complex mechanical structures, introduce parasitic elastic joints with parasitic resonances effects.

2.1.1 Elasticity effects in transmissions

Industrial gearboxes and transmissions are complex mechanical systems. The presence of multiple reduction stages can introduce multiple resonances. Since the gear inertias are much smaller than the applied load inertia the induced high frequency resonances may be neglected. The gear elasticity usually introduces one dominant low frequency resonance. We assume gear elasticity as concentrated in the joint and represented with one spring. Gear and transmission inertias partially contribute to the equivalent motor inertia as they appear as rigidly linked to the motor shaft. Long transmission shafts are internal to one of the links and contribute, as were at rest, to the link tensor of inertia, mass and barycentre (see "rigid" body mass properties). Meanwhile they add additional inertial and friction torques because are not at rest at all. These effects can be modelled in the elastic transmission model as inertia and friction blocks added both to the motor (gear input) shaft and to the load (gear output) shaft.

2.1.2 Distributed link deformation

Distributed link deformation can be modelled as an Euler-Bernoulli beam in rotation [1]. The beam (**Fig. 1**) has length L, uniform density ρ, Young modulus · cross-section inertia EI, actuator inertia J_0, payload mass mp and inertia Jp; reference frames: (X, Y) absolute; (x, y) moving with instantaneous centre of mass CoM. These are assumptions and definitions:

- beam undergoes small deformations of pure bending type in the plane of motion
- (no torsion or compression)
- bending deformation $w(x, t)$, with $x \in [0, L]$, is directed along the y direction
- rotational inertia of beam sections is neglected

Other relevant angular variables are:

- position $\theta(t)$ of the CoM (not measurable, but convenient);
- position $\theta_c(t)$ of the tangent to the link base (measurable gear output shaft);
- position $\theta_t(t)$ of a line pointing to the beam tip (measurable in several ways).

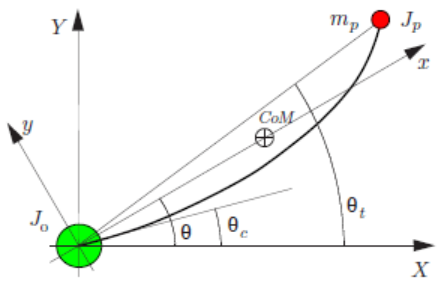

Fig. 1. Euler-Bernoulli beam in rotation

We assume that:

> ***A1)*** the difference $\theta_t(t)$-$\theta_c(t)$ is small compared to $\theta(t)$-$\theta_c(t)$ and we introduce the rough straight line approximation of the beam bending deflection: the link is still considered as rigid with position $\theta(t)$ of the *CoM*. $\theta(t)$-$\theta_c(t)$ is considered tangent to the link base and is added to the transmission elasticity deflection. Link bending and gear deflection will be represented as an elastic joint linking the actuator output shaft to a rigid link.

2.1.2 Parasitic resonances

Parasitic joint model represent unexpected elastic deformations concentrated in some part of the robot link chain. Not ideal mechanical constraints can originate parasitic joints. These EJ are responsible for resonance modes not introduced by actuated EJ. We introduce the extended higher order dynamic model with both actuated and parasitic EJ. In **Fig.2** the block diagram of the interaction (linear model approximation) between an actuated and a parasitic EJ is shown. The interaction is introduced by elements of the extended model inertia matrix. We will show an application of this model for a joint stiffness (link bending + gear deflection) identification.

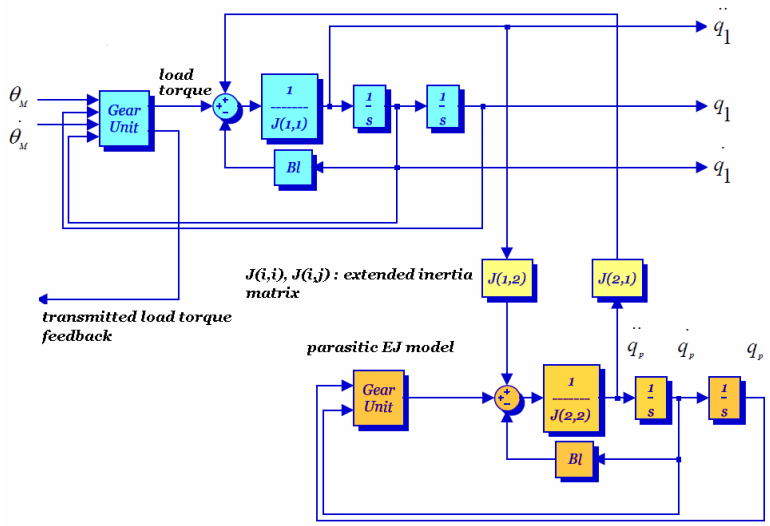

Fig. 2. interaction between parasitic and actuated EJ

2.2 EJ Robot dynamic modeling

To introduce the EJ robot dynamic model, we consider [2]:

- an open-chain robot with *N* (rotary or prismatic) elastic joints and *N* rigid links, driven by electrical actuators;
- motor variables $\theta \in R^N$ (as reflected through reduction ratios) and link variables $q \in R^N$ as generalized coordinates; $(q-\theta)$ represents both the gear and the link bending deflections and q defines the positions of link centers of mass;

Standing assumptions:

- ***A2)*** small displacements at joints (linear elasticity domain);
- ***A3)*** axis-balanced motors (i.e., centre of mass of rotors on rotation axes);

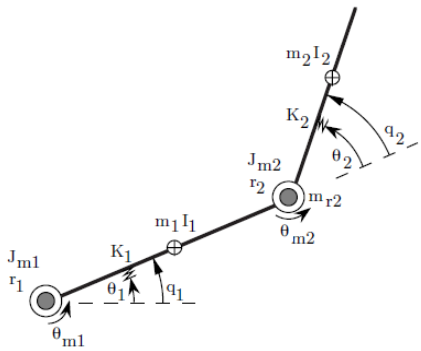

Fig. 3. EJ model for a two links planar robot

- link kinetic energy and link potential energy due to gravity (including the mass of each motor as additional mass of the carrying link)

$$T_l = \frac{1}{2}\dot{q}^T M(q)\dot{q} \qquad U_g = U_g(q) \tag{1}$$

with symmetric, positive definite inertia matrix *M(q);*

- potential energy due to joint elasticity

$$U_e = \frac{1}{2}(q-\theta)^T K (q-\theta)^T \tag{2}$$

with diagonal, positive definite joint stiffness matrix *K;*

- ***A4)*** simplifying assumption (Spong, 1987): angular kinetic energy of each motor is due only to its own spinning with diagonal, positive definite motor inertia matrix *J* (reflected through the reduction ratios: $J_i = J_{mi} r^2 i$, $i = 1, ...,N$)

$$T_m = \frac{1}{2}\dot{q}^T J \dot{q} \tag{3}$$

- system is Lagrangian and the Lagrangian *L* satisfies the usual vector equations:

$$\begin{aligned} &L = T - U = (T_l + T_m) - (U_g + U_e) = L(q,\theta,\dot{q},\dot{\theta}) \\ &p = (q,\theta) \in R^{2N} \\ &\tfrac{d}{dt}\left(\tfrac{\partial L}{\partial \dot{p}}\right)^T - \left(\tfrac{\partial L}{\partial p}\right)^T = u \end{aligned} \tag{4}$$

being $u \in R^{2N}$ the non-conservative forces/torques performing work on *p*. Adding to the model the dissipative terms, the elasticity internal damping and the diagonal matrix *Ntr* for joint reduction ratios, we obtain three equations (link, joint transmission and motor equation):

$$\begin{aligned} &M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + f_l(\dot{q}) + \beta_l \dot{q} = \tau_l \\ &\tau_l = K(\theta - q) + \beta_{ml}(\dot{\theta} - \dot{q}) \qquad\qquad \theta = Ntr^{-1}\cdot\theta_m \\ &J_m\ddot{\theta}_m + \beta_m\dot{\theta}_m + f_m(\dot{\theta}_m) - Ntr^{-1}\cdot\tau_l = K_t \cdot I_m \end{aligned} \tag{5}$$

K_t is the diagonal matrix of motor current to torque gains, $I_m \in R^N$ represent the motor current vector. Electrical drive dynamic shows very high frequency dominant poles not taken in account. We consider I_m as the system control input. The vector $\theta_m \in R^N$ is the usually measured output (motor shaft mounted encoder/resolver position sensor), while *q* is the usually not measured but more appropriate system output. The equations (5) introduce a more general class of industrial robot models. With these object oriented models it is possible to represent also closed-chain robots (with multiple loops) and mechanically coupled joint transmissions:

$$\tau_l = W^T \left[K(\theta - Wq) + \beta_{ml}(\dot{\theta} - W\dot{q}) \right] \qquad (6)$$

2.3 Standing assumptions and field results

Assumptions ***A3)*** and ***A4)*** hold for industrial robots. To show ***A1)*** and ***A2)*** usually hold, we shortly introduce and discuss some field results. Many works and textbooks have been published dealing with "rigid" robots dynamic parameter identification (see [3],[4]). For this reason methods for the development and parameter identification of the first rigid link equation (5) are not outlined here. We focus our attention on stiffness matrix *K* identification. To do that, we get linear model approximation for model (5):

- we assign to the joint positions *q* some fixed nominal values q_0,
- we consider small velocity condition $\dot{q} \approx 0$,
- we consider gravity and not linear friction as exogenous disturbances for linear m.

From (5) we get:

$$\begin{aligned} &M(q_0)\ddot{q} + \beta_l \dot{q} = \tau_l \\ &\tau_l = K(\theta - q) + \beta_{ml}(\dot{\theta} - \dot{q}) \\ &J_m \ddot{\theta}_m + \beta_m \dot{\theta}_m - Ntr^{-1} \cdot \tau_l = K_t \cdot I_m \end{aligned} \qquad \begin{aligned} &q = q_0 + \delta q \\ &\theta = Ntr^{-1} \cdot \theta_m \end{aligned} \qquad (7)$$

$M(q_0)$ introduce coupling in the system. For each joint *i*, *i = 1,...,N*, a joint positions set Q_0 exist such that:

$$q_0 \in Q_0 \Rightarrow M_{ji}(q_0) << M_{ii}(q_0), i \neq j \qquad (8)$$

For $q=q_0$, the matrix $M(q_0)$ is almost diagonal for joint *i* ([5],[6]), joint *i* is almost decoupled and it is possible to identify a I_{mi} to $\dot{\theta}_{mi}$ low order transfer function. From the identified tr. f., provided that the $M(q_0)$ is known, it is possible to get good estimate of the element K_{ii} of diagonal stiffness matrix as solution of a not linear curve fitting problem. If $q_0 \notin Q_0$, it is, anyway, possible to get good joint decupling effect (see [6]) by suitable independent joint servo control design and tuning (actuated joint mechanical resonance damping).

In **Fig.4** (left) we see the stiffness measurement set-up (ax 1 of a COMAU NHJ 370-2.7). An alternating torque of max amplitude *9358.74 Nm* is applied by a force *F = 3924 N* applied at a distance *b=2.385 m*. Distributed deformation has been considered (deflection measured near the TIP). The diagram in **Fig.4** (right) shows that dead zone model plus stiffness linear model approximation (dash line) still hold. Assumption ***A2)*** can be relaxed: linear model roughly hold for "large" (*0.004 Rad*) displacements. The linear stiffness value is *K= 2751760.18 [Nm/Rad]*. Deflection at joint base (transmission output) has been measured: K_{base}*= 9991068.0 [Nm/Rad]*. The distributed arm deformation can be modelled by equivalent additional stiffness K_{dad} = *3796605.85 [Nm/Rad]* and take over the transmission stiffness. Assumption ***A1)*** roughly still hold for modelling ax1.

Fig.5 show ax1 linear (closed loop) identification model and the related mechanical model fit. The Bode plot of current I_{m1} to motor speed $\dot{\theta}_{m1}$ tr. f. shows the low frequency mode (*4 Hz*) induced by joint 1 elasticity. The reduced 3rd order model zero frequency is a function of stiffness: $\omega_{ar} = \sqrt{K_1 \cdot M_{11}^{-1}(q_0)}$. To fit the identified tr. f. as a frequency domain function of mechanical parameters (as actuated EJ stiffness K_1 and parasitic EJ stiffness K_p), we used the 5th order model depicted in **Fig.2** and a Simplex based least square fitting procedure (see [6] for details).

The K_1 estimated value (see **Table 1**) is quite close to the measured one (**Fig.4)**. Since these are archetypal results for industrial robot modeling, (7) and the related not linear class of models (5) can be considered "good enough" tools for system analysis and realistic simulation.

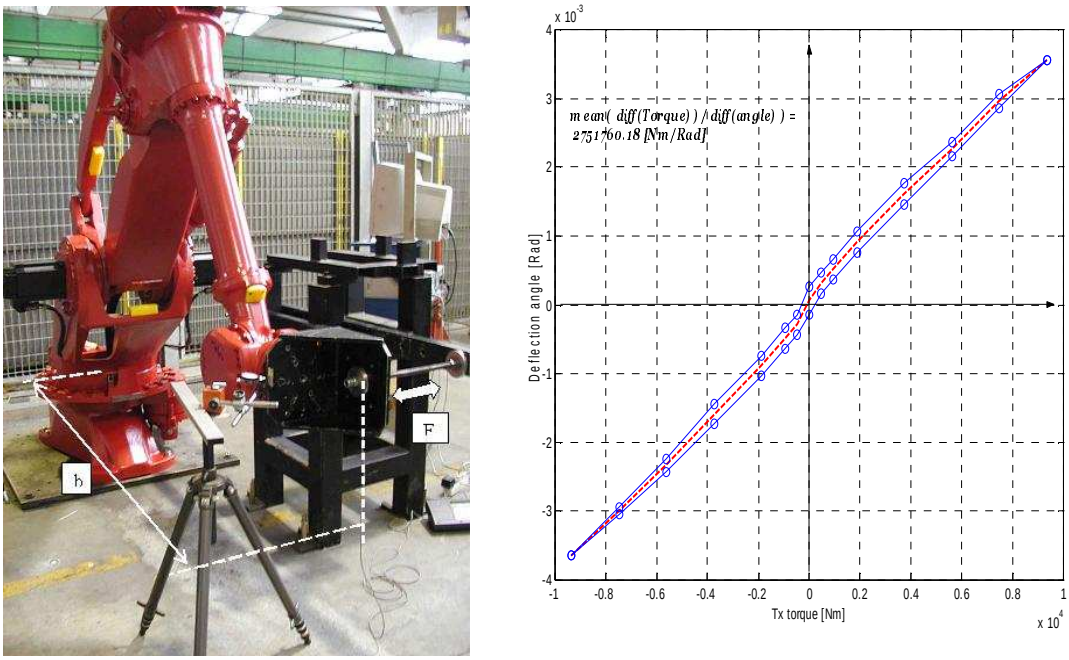

Fig. 4. left: ax1 (static) stiffness measurement set-up – right: joint deflection vs. applied torque diagram

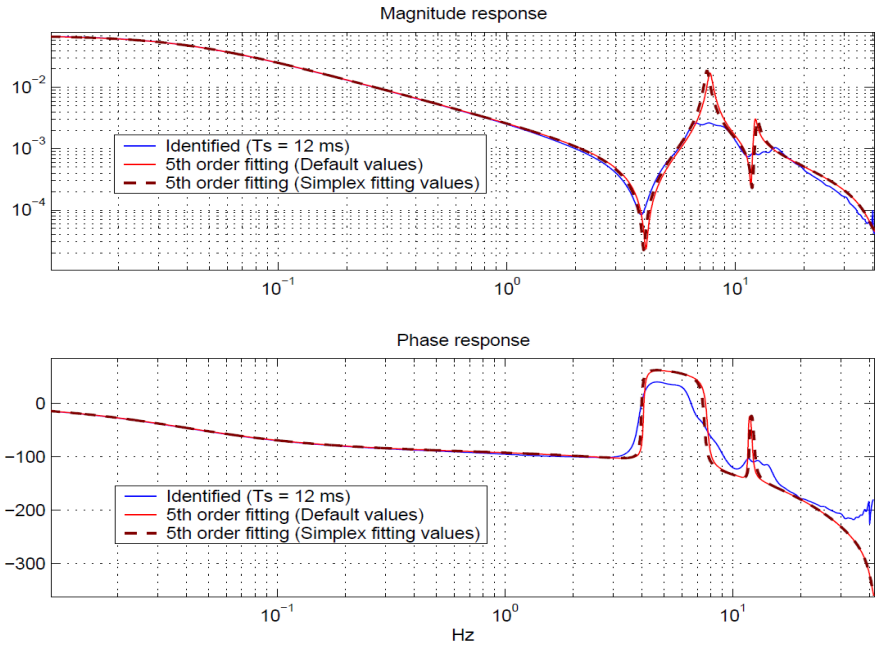

Fig. 5. NHJ 370-2.7: ax1 current I_{m1} to motor speed $\dot{\theta}_{m1}$ transfer function

Table 1. Mechanical parameters estimate

Main physical parameters	Value	Unit
$M_{11}(q_0)$	3715.2411	Kgm^2
K_1	2742905.5	*Nm/Rad*
K_p	424341.7	*Nm/Rad*

3 Sample simulation results

Simulation results for COMAU NM 45-2.0 robot are reported. It is a 6 degree of freedom, open chain robot for payload up to *45 Kg* with *2.0 m* reach. NM is a robot both for manipulation and technological and accurate processes. NM model shows 6 actuated EJ and 2 main parasitic EJ. The simulation is related to the execution of the Smith's path. This ISO test path, laying on X-Y plane, is intended for checking accuracy in high speed, "fly" type move execution. Reference, real and simulated 3D space trajectories are reported relative to x-y plane (**Fig.6**), x-z plane and y-z plane (**Fig.7**). For the simulation we did not used the extended 8 degree of freedom (6 EJ and 2 parasitic EJ) and did not use static friction simulation (only columbic and viscous friction simulation blocks were used). Simulation results are anyway quite realistic in this case.

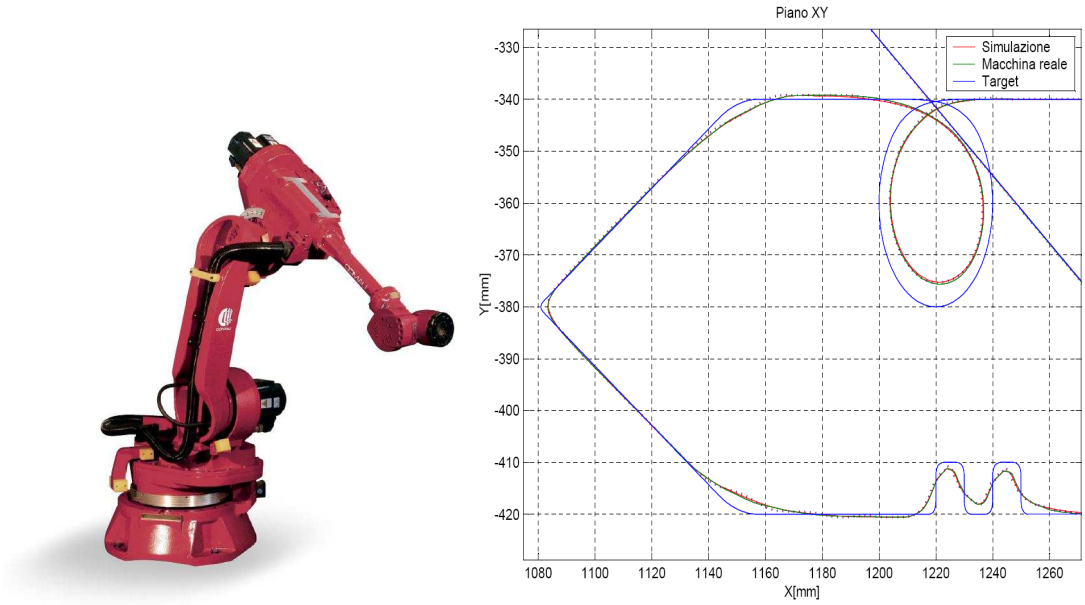

Fig. 6. left: COMAU NM 45-2.0 - right: Smith's cycle XY plane results (most significant details)

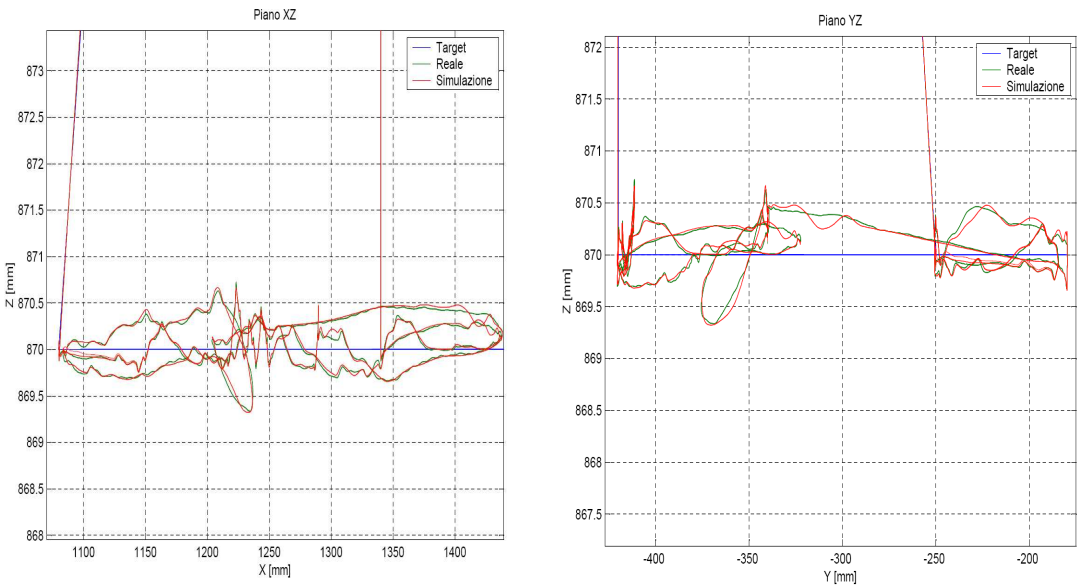

Fig. 7. Smith's cycle XZ and YZ plane simulation results (most significant details)

3.1 Software implementation examples

The model class **(5)** is a general concept. In 2002 COMAU Robotics started to develop for internal use an object oriented Matlab-Simulink Robotics Library implementing this class (**Fig.8 left**). During the ACODUASIS Project (funded by the European Community in the period 2003-2005, under the specific research and technological development programme "*Promotion of innovation and encouragement of SME participation*") the same object oriented library concept was transferred (**Fig.8 right**) into the robotics oriented version of *EICASLAB*, advanced simulation and control design software tool (EICAS Automazione s.p.a., 2005).

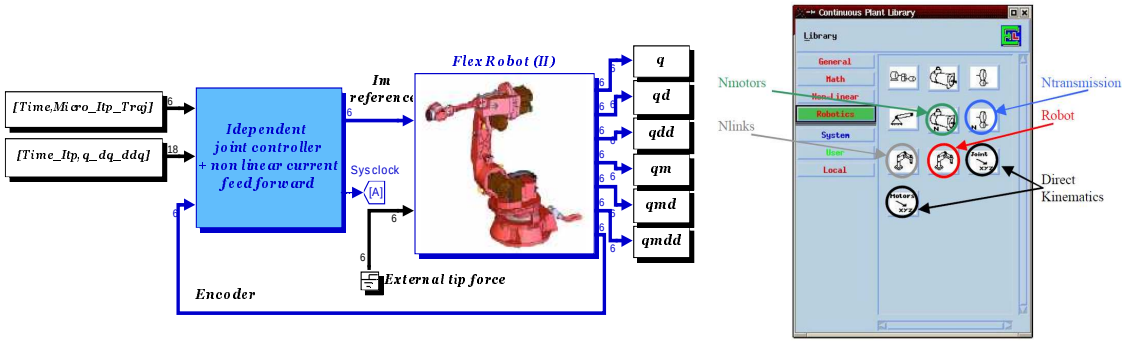

Fig. 8. left: COMAU NM 45-2.0 simulator – right: EICASLAB: the Robotics Library

With these object oriented libraries, the user has the possibility to describe completely the cinematic and dynamic behaviour of an industrial robot, composed by a generic chain of links, joined by prismatic or rotational joints, and structured in an open or closed loop chain. The description of the robot is just a parametrical description (object attributes specifications) and no code must be written (object methods already defined). It is possible to do simulation and evaluation of robot performance both in the joint coordinates space and in the Cartesian space. NM simulation results have been obtained using the COMAU Robotics Library.

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