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Instrumental Robots Design with Applications to Manufacturing

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7.1 Introduction

Instrumental robotics are developed to provide functionally oriented equipment, having duty adapted activity performance figures in order to accomplish sets of required tasks, with proper autonomy ranges. Basically, robots characterize the domain of intelligent automation, supplying the "active" adaptation of the actuating, handling, grasping, or machining dynamics. Active behavior innovates conventional feedback automation, making it possible to modulate the dynamics as a case arises, while tasks are performed. It is usually understood that adaptivity has to be related to outfit and reset actions, enabled with "knowledge" of the ongoing duty sequences and surrounding influences. Furthermore, task-driven equipment is usually concerned with "uncertainty," since it's end-effector is interfaced to the structured "external" world. The uncertainty is overridden by knowledge-intensive techniques, that mainly exploit system hypotheses to drive the manipulation dynamics with due account for instance, of the modeled nonlinear inertial couplings and observation data to modify the current behavior while counteracting the external off-setting influences.

The domain of instrumental robotics is characterized by its task-dependence by the detailed specification of operation duties, and by the current recognition of execution charges. The robot behavior is mainly assumed to evolve according to structured patterns, i.e., distinguishing the related developments from those that are typically investigated in the field of the artificial intelligence applications and aiming at autonomous agents interfaced to unstructured environments. In this field, the operation autonomy presumes on-line task-planning, performed by exploiting goal-oriented bent and self-learning abilities to generate (turn by turn), proper activity patterns. Autonomy under-emphasizes robots as rigs that do jobs. Matching a "generic" robot to a task requires costly interfaces, a complex program, and cannot reach "optimal" schedules. Functional bent due to instrumental turn, on the other hand, reaches effectiveness which resorts to off-process task-programming by acknowledging "optimal" activity modes, prearranged to secure the accuracy, dexterity, efficiency, and versatility figures required to exactly fill out the wanted set of tasks (and not aim at some generic goals).

The idea behind functional bent is equivalent to a paradigm in robotics stating: "*as soon as a task is acknowledged into a series of instructions, then equipment can be devised to do it*." Actually, the ability to recognize operation models might become restrictive: a person could be able to perform "undefined" tasks, filling gaps with skill; better plans could be stated moving the "intelligence" from manufacturing to artifacts' redesign. The two issues are different and the second has entrepreneurial value. When instructions lack a quantitative basis, it cannot attempt to perform an audit for quality data or artifacts would be delivered with unpredictable specification; and, when product-and-process are simultaneously poised by reengineering, economic and technical criteria could be stated quantitatively to recognise good or bad artifacts. Economic considerations make understanding that the functional bent might become misleading, if built as an unnecessaryly complex technology-driven solution. Artifacts really need to be offered with "fit-for-use" properties and should be designed with bound operation range and application scope. Activity outlook, rather than sophistication, is the winning alternative of instrumental robotics, shifting the concern on adapting products to improving the manufacturing effectiveness and the client's satisfaction.

The Design Cycle for Instrumental Robots

The integrated approach to instrumental robotics attempts to simultaneously define activity modes and functional devices. The design of task-driven robots is a very exacting request to achieve the required operational performance with a return-on-investments benefit. It is incumbent on the designer to set operational rules that assure the fulfilment of the charges as specified by the activities model. It is understood, that outside such range a task-driven robot does not operate properly. It might possibly acknowledge a set of feasible tasks and progress as far as possible or, more correctly, generate "help" or "warning" messages. The integrated design cycle in instrumental robotics, Fig. 7.1, will iterate the following five steps:

1. Specification of the behavioral requirements of the tasks need be executed, with choice sets of competing activity modes so that technology-driven solutions will demonstrate their consistency (through prototypal implementations or the like) and could be classified in terms of cost-driven assessments.
2. Model the operational performance of the hypothesized robotic equipment, in connection with the acknowledged task-oriented specifications. The setting of consistent manipulation

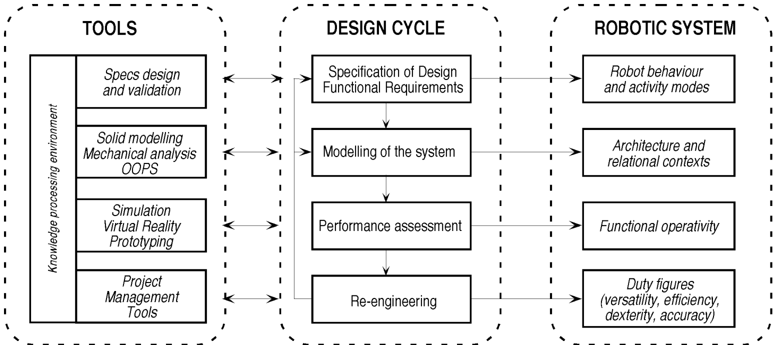

FIGURE 7.1 The design cycle of instrumental robots.

architectures and the (parametric) generation of the related structural and functional contexts are linked to each others.

3. Assess the characteristic features of each solution, with checks on the functional operativity (activity mode and process lay-out) and on the discriminating patterns (technological details and performance achievements) to reduce the development costs. This step exploits simulation and virtual reality checks while it uses prototyping only for critical components.
4. Reconsider the duty figures (versatility, efficiency, dexterity, and accuracy) and of the preset constraints to evaluate hidden merits and dearths. The step requires careful testing on the specifications and on the models, particularly when the prospective instrumental robot suggests 'new' operation modes as compared to conventional (anthropocentric) robotics.
5. Iteration of the cycle, whenever appropriate.

The steps cannot be undertaken unless the behavioural specifications, the relational contexts, the performance assessments, and the reengineering options are quantitatively recognized. Design steps profit from computer aids, supported at different levels of details and the functional and structural models of the proposed robotic fixtures; the addition of "helps" manage the decision loops at the users' interface. Functional bent is a powerful means for the choice of efficient instrumental robots when the design starts conceptualizing with all available data. Due to task dependency, processing of the supporting knowledge is needed along the life-cycle of the fixture: to program duty updating, control fitting, activity modes planning, and to transfer the pertinent data each time the robot's charges are modified (as a different class of tasks has to be accomplished). The computer aids are essential to the robot, since the final set-up's effectiveness depends on the duties actually enabled.

To design instrumental robots is a challenging process using technical and economical targets. Technical concern leads to overemphasizing robotic capabilities, increasing sophistication, and pushing the functional bent to make complex tasks feasible. The return-on-investments criteria need to redefine artifact's construction and manufacturing actions so that robot and duty can be balanced within the reach of "lean" engineering. A clear division between robot and task does not exist. That is why one should be in the position to assess advantages of "advanced" options in order to start reengineering and establish the solution that matches any particular request. Basically the design of instrumental robots could split according to two tracks:

- One design investigates technology-driven options and, mainly by computer simulation, looks for "advanced" setups fit to perform any prospected task no matter how complex, joining "interfacing" equipment and software to achieve the goals, and the issues transferring "exaggerated" ability to robots. This can be recognized on the condition that the adequacy for manufacturability is previously fully analyzed.
- Another explores how fit-for-use artifacts could be designed to favor manufacturing and, simultaneously, how processes could be modified to produce them with the available equipment. The

issues possibly slow down innovation, setting aside the features capable of upgrading product quality or improving plant productivity.

The second track faced by manufacturing engineers is at the shop-floor level, aimed at flexible automation with the economy of scope rules. An example of typical issues in "intelligent" settings is given by the authors in the chapter "Techniques in computer-integrated assembly for cost effective developments" [MAC98]. The first track is mainly dealt with in this chapter. The organization of the matter bears the following scheme:

- A section recalls the main features of the issues achieved by computer simulation. The presentation avails itself of an extended programming aid (the 'SIRIxx' set of packages) properly generated to offer opportunities for experimenting sophisticated solutions.
- A section considers alternatives for upgrading functional bent to emphasize process and economical dependence and exploring simultaneous engineering and hardware-software modularity (i.e., standard mechanical parts, normalized command, and/or mobility).
- Further (two) sections give details about example developments aiming at robots with advanced control opportunities (dynamical nonlinearity compensation, redundant position/force control, etc.) and robots with sophisticated manipulation architectures (multiple robot configuration, redundant mobilities robots, etc.).

7.2 The Design of Function-Oriented Robots

Robots got their name from a Slavish root meaning "heavy labor," thus, they are developed to replace manual workers. They should be endowed with handy skills and training ingenuity "sufficient" to accomplish the considered tasks. A robot and it's duty are inseparable, but quite soon the difficulty of quantitative and deterministic job descriptions that humans were able to perform appeared. Designers started to equip the robot with further capability to fill the gaps in the job description. This innovation moved to end fixed automation and special-purpose equipment and to use computer intelligence for flexible automation and multi-task equipment. The achievements are technology-driven issues and business-driven economic patterns that appear as constraints to slow down replacements until return-on-investment (ROI) is verified.

The problem, however, is not just economical or technical. To assess its "fitness-for-purpose," the fixture ought to exist and be tested in the proper surroundings, to verify potential and effectiveness. The checks should cover, besides instrument functional appropriateness, the soundness of robot duties in terms of scheduled goals and task usefulness and increase process reliability and product quality. The design of function-oriented devices, on these grounds, splits into a series of accomplishments (see Fig. 7.2); of course, the separation by conceptual stages or detail levels is mainly done for academic purposes. The practical development of "new" robots, before "new" applications, is undertaken with the know-how of previously tested equipment. A design cycle can be started at any point, neglecting noncritical details or postponing underspecified phases. Phases in re-engineering, nevertheless, can only be started with "sufficient" knowledge on both robot technology and simultaneous engineering. In this chapter, attention is focused on robot technology; however, for instrumental robotics, the design will move from an "effectiveness" model, with "price-time" figures, to a return-on-investment model by monitoring process-added value and productivity performance. If a robot costs too much or takes too long to do the tasks, it will fail in the marketplace. The "effectiveness" model leads to recognition of the close binding of robotics and design and the critical support provided by CAD opportunities.

Conceptual Design of Task-Driven Robot Arms

The design of task-driven equipment aims at robots with operation capabilities and planning options to allow feasibility of the desired charges (regardless of the complexity or product-process consistency). The subject has been tackled from different standpoints related to the handling architectures [BeP97],

To acknowledge the robotic fixtures consistent with the task to be performed by means of a design cycle, undertaken at different levels of detail	
task-level assessment	to specify the corresponding operation details and to explore the consistency of the detailed sequences
task-level programming	to select series of instructions for their accomplishment and to single out manipulation architectures making the programmed charges feasible
operation-level assessment	to specify the commands making coordinated motion feasible and to investigate actual governing strategies
operation-level verification	to evaluate actual performance and robot's fit-for-use according to the tasks to be performed
To acknowledge task sequences consistent with the goals of the processes where robots are included as instrumental fixtures, by iterated design cycles	
goal-level re-engineering	to evaluate products' alternatives preserving or improving customer's satisfaction with 'simplified' technical specifications
process-level re-engineering	to explore the design-for-manufacturing changes, which increase the effectiveness of the production cycles
equipment-level re-engineering	to find out competing instrumental solutions, with better return on investment figures
programming-level re-engineering	to establish software tools, which would expand robot's operation or efficiency ranges

FIGURE 7.2 Conceptual stages and detail levels of the robot design.

[LII96b], [LYK97], [MAC93], [RoB97]; to the manipulation dynamics [Asd88], [AsH79]; or to the path planning [ACH95], [Alg97], [CCS91], [Whi69b], [ZOY96a], [ZOY96c] requirements, and a lot of practical know-how is available. Example results provide hints on the evolution of the design in robotics, from advanced technology-driven fixtures, to (just technical) fit-for-purpose solutions. Topics are reviewed following the authors' experiences and are presented, without presuming completeness, considering example issues, starting from abstract users' interface requests and entering into technical details that make possible the planned tasks with increasing performance.

- *Path planning and architectural analysis*. Path planning deals with the mapping of the end-effector set-points defined in the work-space, into actuation commands fed to each joint. In general, the effector should possess six degrees of freedom (three angular and three displacement co-ordinates) and the arm needs to combine the related number of powered mobilities. The robot is thus, a multi-variable system requiring adapted inputs for steering the tip location and attitude. Six powered mobilitiy manipulators are basic references for establishing kinematic path-planning problems.

The forward (to the work-space) and the backward (to the joint-space) kinematics can be stated after the manipulation architecture is selected. These (algebraic and nonlinear) transforms are:

$$x = f(q) \quad q = g(x) \quad q \in Q^n \quad x \in X^m \tag{7.1}$$

where x-work-space coordinates and q-joint-space coordinates. The kinematic inversion is generally unsolved, unless a few geometric restrictions are introduced to specialize an algebraic solution (as exemplified by the later mentioned SIRI-CA package).

The availability of the forward and backward kinematics (7.1) can immediately be used to explore the considered architecture's worthiness to accomplish the given set of tasks. The analysis has to be done as the initial job of the design cycle; sometimes less than six mobilities could be sufficient and "reduced" degrees-of-freedom robots are "good" choices. Sometimes, obstacles in the work-space or in the joint-space are properly avoided with additional powered joints and "redundant" mobilities robots are a "better"

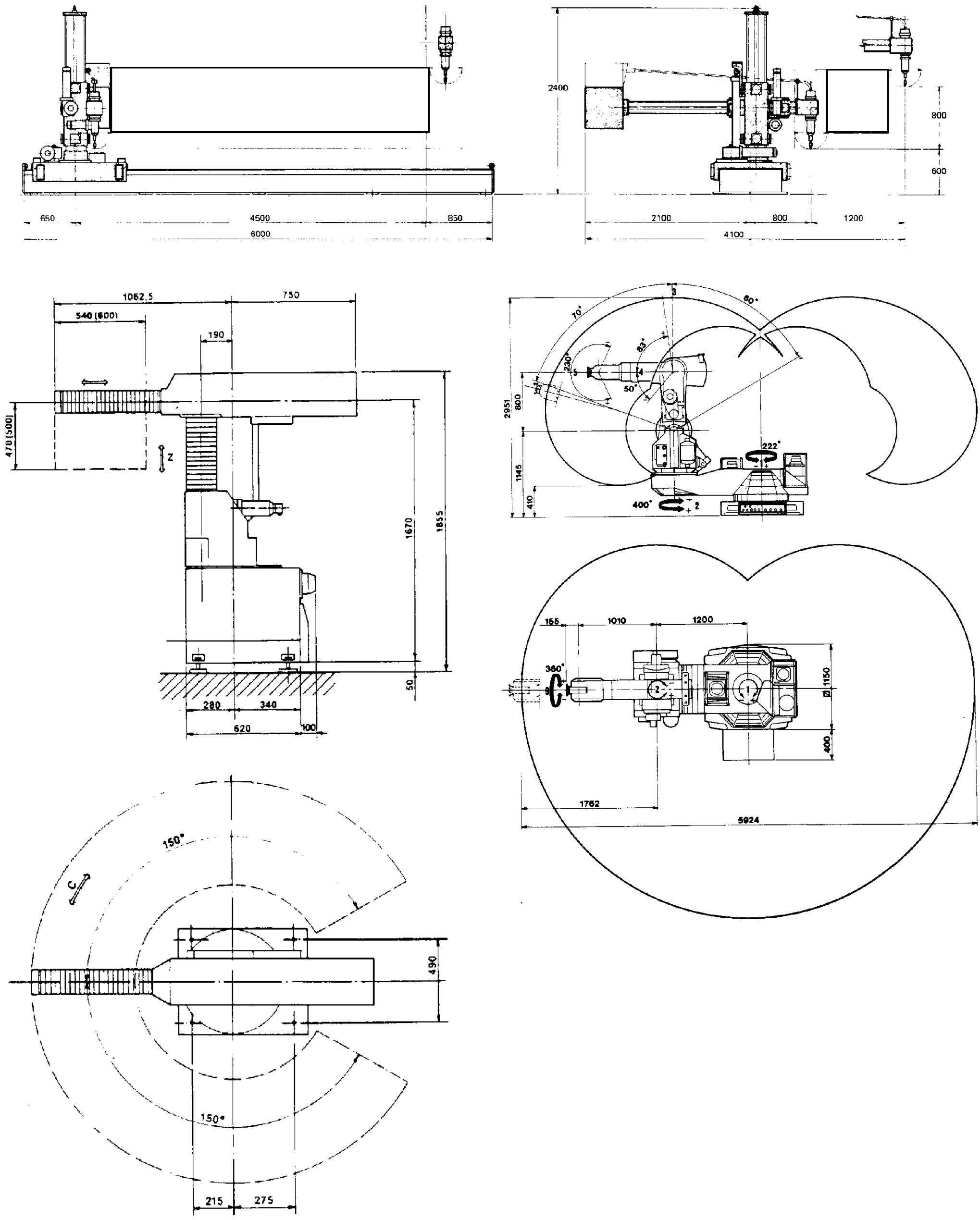

FIGURE 7.3 Example of robot architectures and related work-domains: (a) cartesian structure; (b) cylindrical structure; and (c) articulated structure.

option. The six-mobilities case is, however, basic reference to begin analyses and to obtain practical descriptions useful for CAD opportunities. The forward kinematics is usually defined with bounded spans of the joint coordinates; the mapping leads to closed domains of the work-space with shapes, (Fig. 7.3), which are related to the robot architectures according to patterns that can be used for classifying purposes.

To simplify the generation of computer solutions, linearized models are considered, assuming that velocity vectors, in both spaces, should steer the tip to smoothly approach the target. For the reference

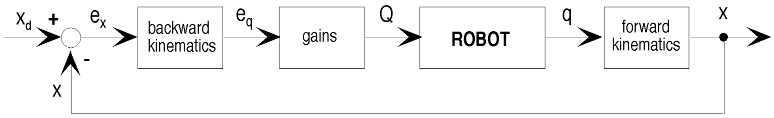

FIGURE 7.4 The work-space incremental control scheme.

architecture of an arm with six sequential mobilities, the so-called 'Jacobian approximation' holds:

$$\dot{x} \approx \frac{dx}{dt} \approx \left[\frac{\partial f}{\partial q}\right]\frac{dq}{dt} \approx \left[\frac{\partial f}{dq}\right]\dot{q} \approx J\dot{q} \qquad \dot{q} \approx \left[\frac{\partial f}{dq}\right]^{-1}\dot{x} \approx J^{-1}\dot{x} \tag{7.2}$$

$$\delta x \approx \dot{x}\delta t \approx J\dot{q}\delta t \approx J\delta q \qquad \delta q \approx J^{-1}\delta x \tag{7.3}$$

Jacobian matrices mapping end-effector's angular velocity (instead of Euler angles' rates of change) can be easily worked out by exploiting the previous relations (7.2). At each point, the Jacobian matrix is computed (as incremental ratio) and (numerically) inverted to enable a rate control, Fig. 7.4 (after the mapping is calibrated).

The approach is not without drawbacks for mapping accuracy and useful tricks are, therefore, explored. The traditional task of programming has been based on "teach-by-doing" and by that way:

- The static calibration is performed with (external) work-space references.
- The path planning may introduce rate compensation (depending on localized trajectory anomalies, on speed biasing influences, etc.).
- The setting of the instructions is trimmed to the specialized charges of each application, without explicitly acknowledging the actual robot behavior.
- The operation scheduling does not require models of the physical world (provided that teaching is fulfilled exactly replicating every work condition).

Time delays always occur with digital controllers related to sampling and processing rate. Unstable or swaying paths could be established, unless commands are fulfilled with no closed-loop meddling. Computer compensation of the time-delays is possible, if robot behavior and coupled surroundings models are stated (with possible account of uncertainty through fuzzy logic), or if sensorized interfaces operate on joints and at the work-space end. The compensation, however, is fixture-dependent and, assuming the approximated mapping (7.2), traceability of calibration tests are run and deviations assessed (by sensitivity analysis) for any of the allowed tasks.

- *Control planning and performance analysis.* Control planning is concerned with the choice of feedback loops to be applied at each actuator to make "dynamics shaping" so that the effector executes the assigned tasks with the "best" effectiveness. Again considering six-mobilities arms as reference architecture, the joint-space dynamics for unconstrained motion maneuvres is given by:

$$Q = A(q)\ddot{q} + B(q) + C(q,\dot{q}) + D(q,\dot{q}) \tag{7.4}$$

where Q is joint actuation force or torque; $A(q)$ is mass matrix of the robot; $B(q)$ is centroid off-set unbalances; $C(q, \dot{q})$ is transport and Coriolis terms; and $D(q, \dot{q})$ is friction and damping terms.

The reference dynamics (7.4) are nonlinear with combined effects of the carried links modifying the driving actuation needed at each joint and to impart a co-ordinated motion for the direct control of the tip. High performance robots are pushed to operate at high speed and acceleration. The dynamic coupling nonlinearities could generate undesired troubles, when feedbacks were established for linearized approximations only.

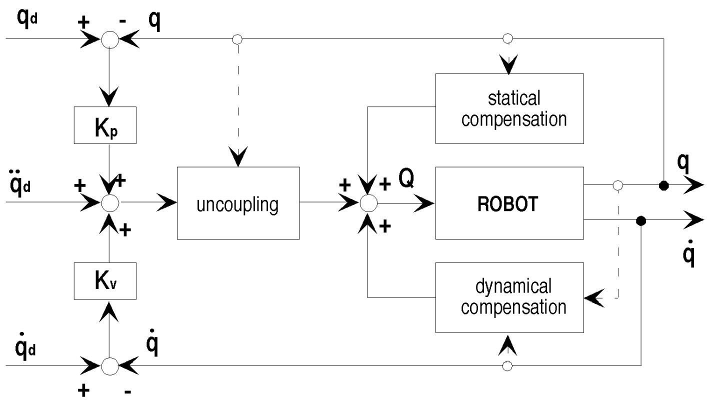

FIGURE 7.5 Joint-based actuation with linearizing and uncoupling feedback.

The free motion joint-based models dynamics has, thus, to deal with the actuation errors:

$$Q = A(q)u \quad u = E_p(q_d - q) + E_v(\dot{q}_d - \dot{q}) + \ddot{q}_d \tag{7.5}$$

where q, $\dot{q}_d$, and $\ddot{q}_d$ are the desired position, speed, and acceleration; E_p and E_v are the gains of proportional and derivative feedbacks.

The suppression of unacceptable back-nuisances is easily performed if the dynamics is properly modeled (7.4) and used as modulation gain, while closing the control loop in the joint-space. This means to exploit the canonical transform which is known to exist for (series of) rigid bodies joined by pivots. The compensation, Fig. 7.5, is easily done on condition, of course, that the architecture of the arm is assessed with known masses, centers of mass, mass quadratic moments, principal directions, etc. After compensation, the actuated joints are uncoupled and can be designed to behave as properly controlled linear second-order blocks. The scheme is a valid option when the coordinated motion control remains a hidden attribute. For instance, tasks are programmed on-line via "teach-by-doing" with due account of the desired performance.

Task programming is presently preferably done off-line supported by intelligent interfaces. The setting refers to the work space and selection of the properly controlled behaviour of each joint needs explicitly deal with the forces and torques transmitted by the distal link. Then, the transforms of the generalized forces can be stated as the dual approximation of the kinematics mapping, leading to:

$$\delta Q = J^T \delta F \quad \delta F = [J^T]^{-1} \delta Q \qquad \text{where: } J^T = \left[\frac{\partial f}{\partial q}\right]^T \tag{7.6}$$

The compensation scheme, Fig. 7.6, can be modified accordingly, providing a clear guess on the operation conditions with, however, additional computations to be performed in real time. The command setting which follows is known as 'transposed local adaptation' since it is operated in the work space, then mapped in the joint space. The strategy gives useful results, when only joint displacements are observed, while the tip location in the workspace, not directly measured, cannot be used for off-setting the task errors.

A different approach tries to avoid real-time reckoning with the local relations (7.2) and (7.5); instead, it exploits current measurements for closing the control loops. As a matter of fact, all robots have encoders to obtain joint (absolute) displacements and to compute joint velocities; with addition of accelerators, (Fig. 7.7), alternative evaluations of the inertial couplings (7.4) are possible, to enable compensation

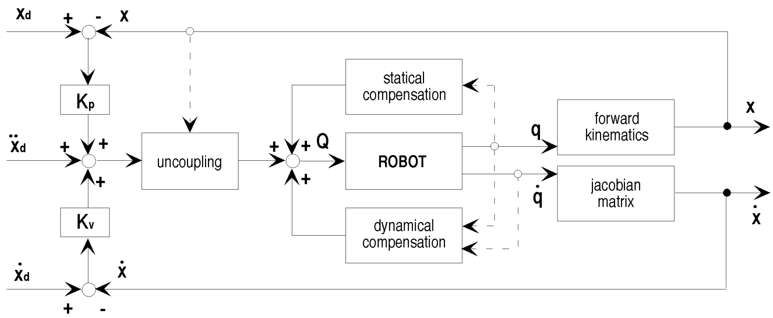

FIGURE 7.6 Work-space commands with compensation of nonlinearities.

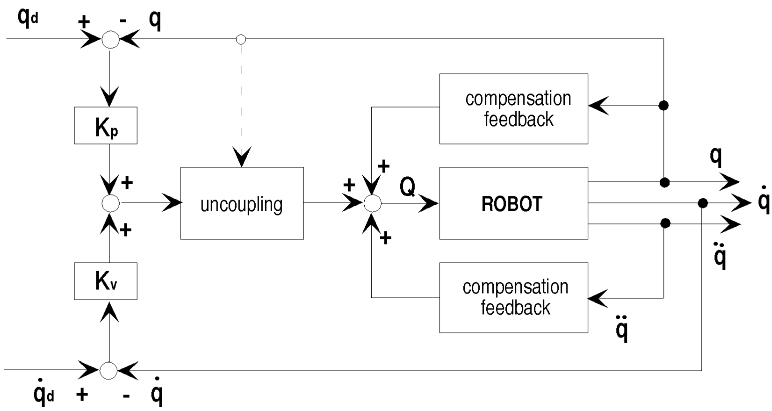

FIGURE 7.7 Sensor-driven compensation of nonlinearities.

feedbacks, or to trim the parametric choices of $A(q)$, $B(q)$,$C(q,\dot{q})$, or $D(q,\dot{q})$. Further opportunities are provided by measurements in the workspace. The direct observation of the tip linear and angular motion has been based on optical devices (cameras, laser sensors, etc.) with, nevertheless, data fusion drawbacks. Relevant advantages are expected by force/torque sensors located at the end-effector for measuring the interactions with the external world. The use of the information, however, needs more sophisticated models, with inclusion of the compliance attributes of the arm (joints, links, etc.) and of the interfaced bodies.

Conceptual Design of Work-Constrained Robot-Arms

The previous paragraph has mainly considered how to drive an arm so that its tip moves along a given path with prescribed attitude. Coordinate measurement machines are good examples of such an approach. Instrumental robots more usually characterized by tasks, with sharply changing charges, and splits the path planning (and control design) to deal with three different models, (Fig. 7.8), for usual duty conditions. Generally, these are reduced to *unconstrained* or *constrained* manueuvers. The third one, dealing with transient constraint manueuvers, needs be accounted for in front of special applications by using computer-aids.

Robot behavior under transient and work-constrained conditions is over-specified when the analysis is limited to rigid body degrees-of-freedom. For practical purposes, investigations are undertaken trying to separate the different influences. In order to be concerned only by a relevant phenomenon (any other input being reduced to be a disturbance); example developments; for instance, are

un-constrained motion maneuvers **(free)** ***navigation path***	The actuation is accomplished on the arm, as isolated system, to bring the end-effector from an initial to a final position and attitude; alternatively, the manipulator is driven in the joint-space without contact with the environment, to make the tip track a trajectory with prescribed orientation and kinematic rules
transient constrained motion manoeuvres ***engagement path***	The actuation faces the discontinuity arising between the navigation and the operation motion; the (collision-like) effects appear as (transient) disturbances and are most of the time neglected by robot designers, provided that suitable over-all stability conditions are granted along the operation work-cycle
work constrained motion manoeuvres **(coupled)** ***operation path***	The actuation deals with the required tasks, mastering the end-effector constrained motion while subject to external influence or disturbance; the arm, driven in the joint-space, is manoeuvring in a constrained environment and needs transmit appropriate interfacing forces and torques, in the work-space

FIGURE 7.8 Characteristic duty conditions during robot maneuvers.

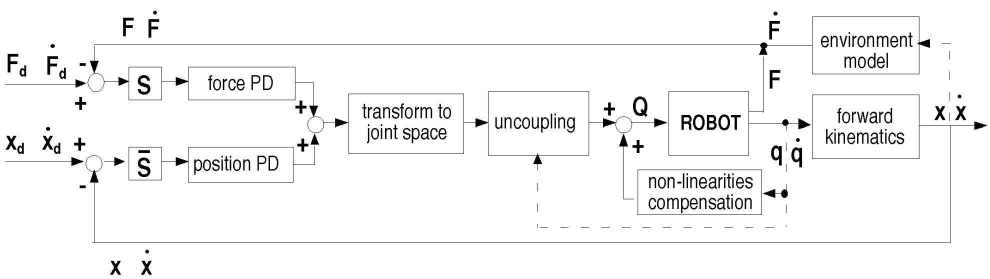

FIGURE 7.9 The combined position/force controller.

- Manipulators, having links and/or joints with (lumped or distributed) compliance, carrying masses (sensors, etc.) and sweeping a region with prescribed paths;
- Manipulators, having rigid (compliant) parts, colliding against compliant (rigid) walls, with different paths and bouncing coefficients;
- Manipulators, with rigid (compliant) parts, performing actions (machining, assembly, etc.) with controlled position and force of the tip.

The conceptual design of robots is said to be concerned by "duty programming" (with "duty" monitored about "task" departure). The addition of "advanced" abilities is still not essential for most of current industrial robot applications. It follows that topics in sophisticated activity modes are well acknowledged, while practical achievements lag far behind. A reason might be the lack of field experience, with clear assessment of actual opportunities. Few concepts are, therefore, recalled to provide hints on how the "duty charges" should be tackled (with respect to simple "tasks") through actuation 'flexibility' (besides "rigid" work-cycles). It can be started by noting that trained and skilled operators, when assembling artifacts, exploit force data to steer the joining motion; thus, performing position control and force modulation. Then, six-axis force-torque sensors are basic rig for anthropomorphic assembly and redundant control strategy applies, Fig. 7.9, by steering the separate feedback loops according to needs.

When one tries the "peg in the hole" task with such a sensorized robot, it may happen that instabilities arise unless the feedback time delay is chosen to match the combined "wrist, peg, and contact zone" stiffness. The force modulation should not be thinner than the measured contact force error. These kinds of instabilities do not depend on the path followed during the co-ordinated motion. By further analyzing the same task, the normal (indenting) and the tangential (friction) components of the contact forces are assessed to understand how insertion progresses along the prescribed directions (e.g., the sequence of Fig. 7.37). Current data is then, available to assess friction and damping effects and to feed engineered compliance so that assembly is fulfilled with delicacy (out of measurement uncertainty) unachievable by people. This means that position/force control is a simple affair of performance: when the combined accuracy, dexterity, efficiency, and versatility figures will be useful for transferring given quality data to the industrial artefact, the option could be checked in terms of return on investment.

Deburring tasks also highly profit by redundant control to grind out weld beads, to finish precision casts, or to honey machined surfaces aiming at constant quality artifacts (not depending on the ability of skilled operators or on the attention to accomplish the job), with cost reduction if burrs removal is granted with accuracy and delicacy. The application is later recalled, with introductory details on the process from a conceptual design viewpoint. The description of tip-to-burr interactions is given by a locally linearized impedance, binding the (generalized) force and displacement components, according to the (approximated) model:

$$\delta\tilde{F}_E = G(s)\delta\tilde{x} \quad \text{with: } G(s) = Ms^2 + Hs + K \tag{7.7}$$

where the reduced inertia M, damping H, and stiffness K depend on the solid zone to be ground and on the actual interfacing characteristics of the powered arm.

Here again, stability problems need, be addressed, due to the contrasting requirements on the normal and on the tangential stiffness figures. The removal of the dithering behavior cannot be extended to avoid the "worst case burr" everywhere in the work space when the deburring robot operates on a fixed artifact because of the contact rigidity between grinding wheel and piece. In spite of that, industrial applications exist (from Japan) with the force-torque sensor technology embedded into six mobilities robots. A better option is possible, carrying the piece by means of a six mobilities rig, so that the contact rigidity is properly modified, process-adapting normal and tangential stiffness. As mentioned, details of the option are later recalled.

The introductory comments of the paragraph give hints about possible "advanced" solutions. The analysis of existing applications to manufacturing (still covering the largest share for instrumental robotics) shows, most of the time quite monotonical replication of manipulation architectures and activity modes. The replication may depend on the functional orientation (meaning that once the task bent leads to an effective rig, it is no use looking for a different one), still the capability of investigating nonconventional architectures and/or behavioural options might suggest how to get out from assessed habits, aiming at 'unexpected' upgrading, by means of alternatives (in particular, if these have already been checked by virtual reality experiments). This is the reason to look for sophisticated models, capable of duplicating the dynamics and control strategies of the instrumental robots, with consistency of details up to the sought technical charges. The models are explored by means of computer aids, leading to comparative assessments and providing, as decision support, a choice of the function-oriented structural settings (component, facility-configuration and command, CFC, frame) and the operation-befit activity modes (monitoring, decision-manifold and management, MDM, frame).

Computer Aids Based on Functional Modeling and Simulation

Computer aids, providing virtual reality experimentation, are a powerful means for fostering the innovation in the field, carefully checking feasibility and effectiveness of new CFC frames and/or new MDM frames, while helping to evaluate the expected return on investment. Computer simulation is a critical means, as the instrumental robotics does not move from anthropocentric functional models, rather it acknowledges task-oriented solutions for the setup of more effective activity modes. Certainly in many cases, robots have been conceived for replacing man, giving rise to replication of 'anthropomorphic devices'; in other cases, they have been developed to perform tasks out of mens' potentialities, giving rise to new fields of 'instrumental robotics,' depending on the conditioning applications, on the transferred level of autonomy and intelligence, and on the actualy achieved performance (accuracy, dexterity, efficiency, and versatility).

The design of operation-oriented robots is a fascinating technical challenge by aiming at the "best" fixtures no matter how complex, providing the conformance to specification is reached and the desired tasks are properly accomplished. The subsequent sections of this chapter try to mitigate the challenge by looking for balanced solutions by having the complexity relieved by the fitness for purpose of the 'economy of scope' approach. By now, the design cycle, Fig. 1, according to the mentioned four steps, is iterated to bring forth pace-wise (performance-pulled and knowledge-pushed) betterments, until 'best' setups are obtained. Iteration progresses with CAD modules supplying virtual-reality display of robot actual dynamics, interfaced with expert modules, as decision support for addressing improved solutions. CAD codes, moreover, help to enter into the details of the predicted functional behavior, to assess the standards to be preserved according to specification, and the entities to be monitored for pro-active maintenance diagnostics.

Several CAD opportunities are available to help the designer, principally,

- General purpose software (such as Pro/ENGINEER series), granting background tools for the buildup of any personalized CAD instance.
- Computer packages suitably arranged into a virtual reality environment to provide systematic support for comparative assessments between competing equipments.
- Computer programs, purposely developed in the framework of a particular project, to give efficient account of the peculiarities of the application.

All three opportunities are useful. The first deserves growing interest since the offered software covers larger and larger CAD details and is endowed with friendly interfaces (costs are the main drawback). The third is largely exploited as soon as the robot equipment is chosen at the suitable level of specification and is the intermediate opportunity best suited to explore for innovation. Typical aspects are considered, hereafter referring to the work carried on by the Industrial Robot Design Research Group at the University of Genova, Italy, which has prepared and used the CAD environment SIRIxx, Fig. 7.10, to develop instrumental robots properly tailored to individual applications.

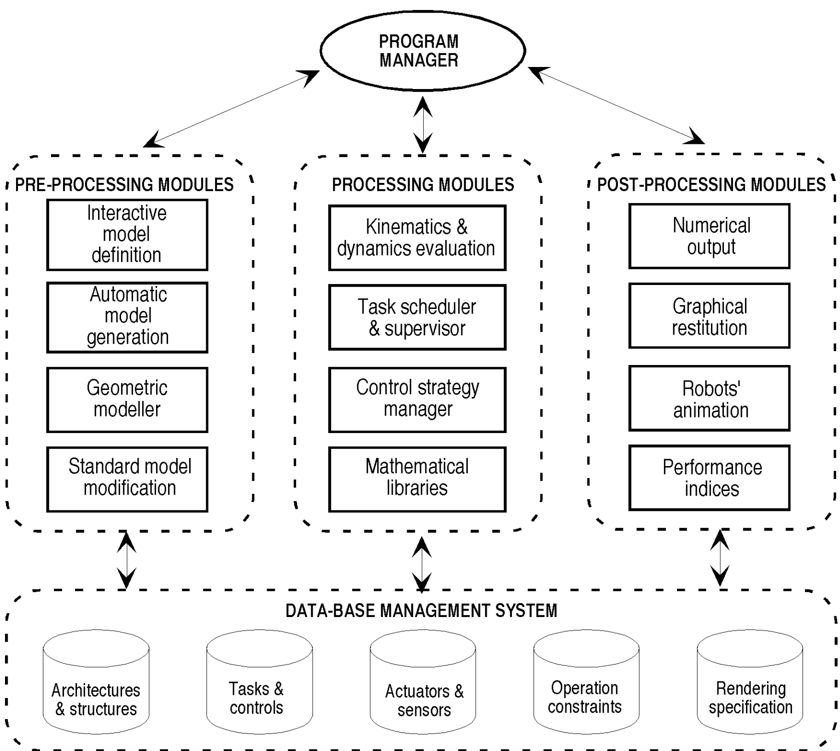

FIGURE 7.10 The SIRIxx robots' design environment.

These packages could be further distinguished by application range; on one side, operation bent is faced as general priority:

- Path planning and architectural analysis are linked with the aid of a set of modules, programmed to generate forward and backward kinematics, for several robots' families.
- Control planning and performance analysis are assessed with the help of a library of modules, programmed to generate example steering strategies, at different levels of complexity.

At higher levels of details, product-and-process matching is explored addressing to less conventional settings and/or more demanding situations:

- Duty planning and function fitting are investigated with the aid of animated displays or robot co-operation to weigh task requirements departures.
- Work constraints and process conditions are tackled by means of control modulation or special effects assessment in front of exacting effects.

This CAD support has been developed over the past ten years with a modular base in order to expand the covered subjects, while preserving computational efficiency. The results have been collected systematically and used as pre-set data for the later discussion of knowledge-based architecture SIRI-XE [ACM88]. The main characteristics of the packages are presented in several papers, with example developments. We defer to the references for details since only a short overview is given hereafter.

The 'SIRIxx' CAD Environment: The Basic Modules

The usefulness of recurrent design-cycle is better explained with examples of the SIRIxx series of packages [AMM87], [AMM90], [ACM91b] which provides useful hints on opportunities and issues underlying systematic investigations. The first group of packages is organised as general purpose CAD support.

- SIRI-CA: providing the usual path-planning objectives. It is built on the availability of forward and backward kinematics of 32 families of open-chain manipulators [ACM86].
- SIRI-AD: assuring the automatic generation of the nonlinear dynamics of open-chain manipulators [AMM84b]. It exploits a step-wise recurrent formulation propagating the dynamical behavior [MMA83].
- SIRI-CL: performing the path-planning and generating the dynamics of three families of closed cinematic chain manipulators. The package presents an oriented structure, exploiting the specialization of the internal constraints [ACM96c].
- SIRI-SC: assessing the robot dynamical performance with competing control strategies [AMM84a], [BMM85]. A modular and extended library of options is provided to help robot control planning.

With the recalled packages, the design cycle evolves, according to the four logic steps of Fig. 7.1, to give rise to sequences of phases, Fig. 7.11, such as:

1. The robot topology is provided by a first specification, employing the application area functional-data and the workspace general-constraints.
2. The payload and mobility requirements provide the main structural properties of the manipulator members and joints.
3. The productivity, with related speed and accuracy figures, makes possible an initial selection of the actuating devices.
4. The task complexity and the functional performance are detailed jointly with the observation schemes to define the control strategies.
5. The architectural consistency is equalized by assessing the robot dynamical behaviour for the set of allocated tasks.

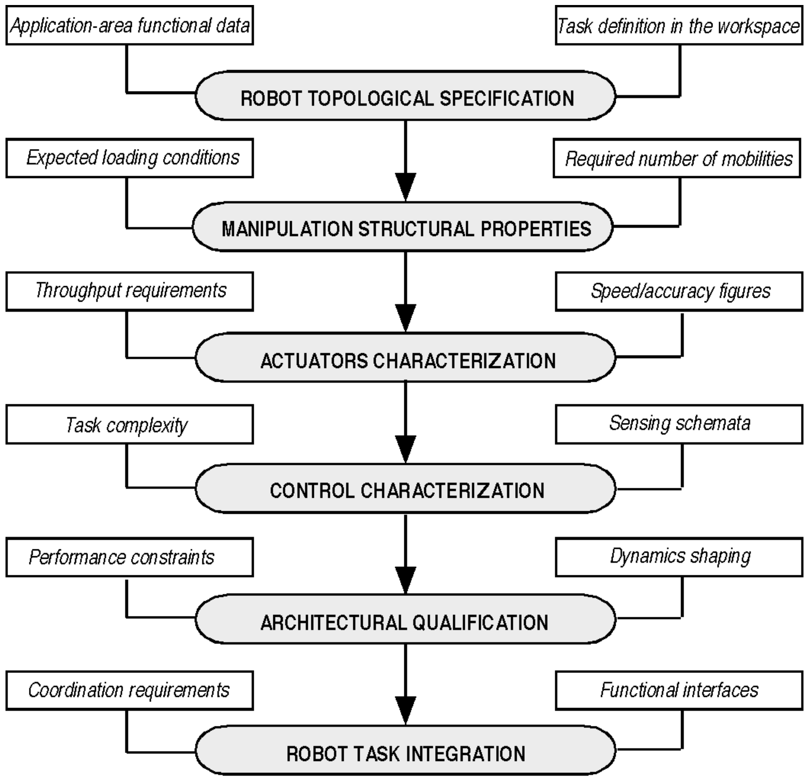

FIGURE 7.11 Basic development phases in the robot design.

6. The job integration of the (software/hardware) resources is performed with concern to the robot communication constraints.

To develop a suitable robotic equipment, an extended background is required which joins the results of the experimentation on existing devices with the investigation on the (structural and behavioral) properties of feasible solutions obtained by a functional description based on the current dynamics. The CAD-environment helps close a set of information loops, Fig 7.12. The designer needs explicit access to all the parameters that may significantly affect the robot operativity. The architectural analysis is required to set the *configuration data,* giving topology and geometrical bounds. In terms of the *structural attributes,* the basic choices concern the

- Actuation data to comply with pay-loads and throughput;
- Observation data to define the appropriate sensing and monitoring scheme;
- Regulation data to specify the control strategies granting the wanted performance.

In parallel, the designer should fix the *conditioning bounds,* specifying the

- Execution data for the management of the scheduled job agendas;
- Co-ordination data for specifying communication and synchronization requests;
- Organization data for prescribing action modes depending on the assigned tasks.

Along with the development cycle, the designer faces interlaced problems, namely,

- The parameters of the functional models (inferred from presumed system hypotheses) should be adapted to improve robot performance with respect to the selected tasks.

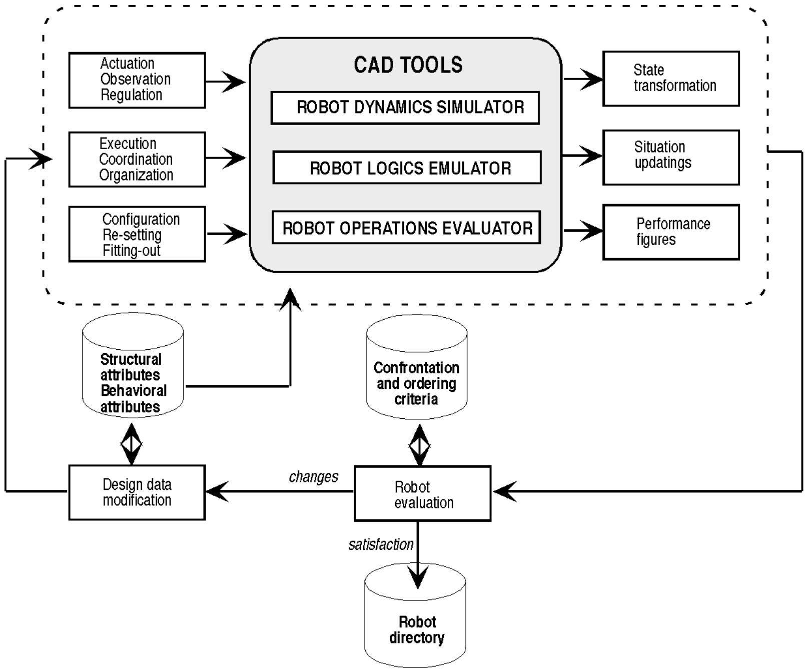

FIGURE 7.12 CAD environment for robot design.

- The models, identifying the task implementation, shall be modified (updating system hypotheses) improving the reference knowledge with account of the conditioning functional criteria.

Typical situations faced by a designer for developing robotic equipment are covered briefly.

- *Architectural analysis*—The setup of the robot layout is, logically, one of the final issues (it is at the fifth phase in Fig. 7.11); production engineers, however, shall directly define a preliminary architecture for their own application by simply considering existing robots (with, possibly, special-purpose rigging). The SIRI-XE framework is available for that purpose. It is based on the X-ARS package [ACM88] that essentially comprises: a *general data-base*, where investigated robots are orderly catalogued into frames with a hierarchical presentation of the available information: a *data-base management block* employed for creating, deleting, or modifying the frames and/or their contents; a *user interface* for interactive operations (through a nested menus sequence) or for assisted operation (through an "expert" block); and an *expert manager* with a rule-based procedural knowledge providing the inference mechanism based on heuristics for the selection of application-consistent robots.

The possibility to broaden, update, and modify robot records is a noteworthy option of the framework. Robot technology is a rapidly evolving area: new devices have to be added; classification criteria, updated; and functional abilities, modified, etc. It is important, moreover, to have an instrument that may be personalized according to the application needs. A database management block is required to help code new knowledge on robot performance under actual running conditions and to expand the structural and behavioural data. The SIRI-XE framework exploits this database management block to implement the ordered recording of existing robots in terms of combined architectures-tasks data. Then the X-ARS procedural knowledge can be employed as expert consultant: in this mode a set of consistent functional features (configurational conditions and/or programming resources) is recommended and the user can accept, reject, or modify the suggestions, updating the robot directory with these 'new' options.

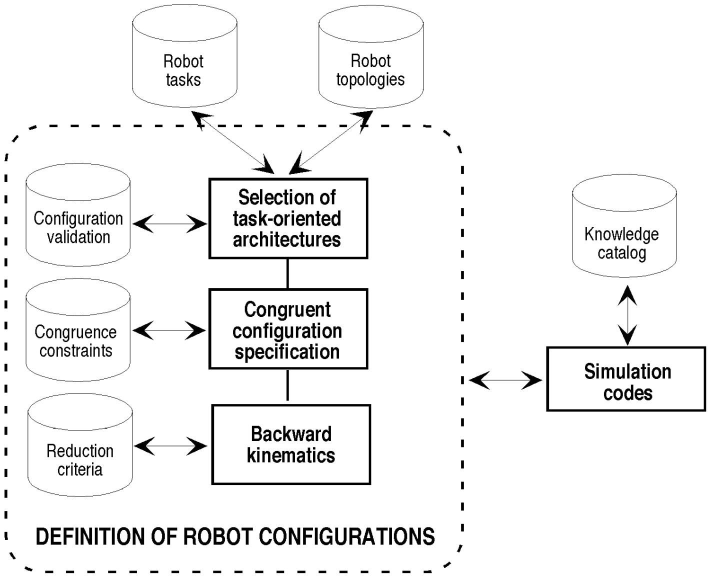

FIGURE 7.13 Selection of path-consistent robot topologies.

- *Activity-modes analysis*—The robot functional characterization depends on the set of tasks to be performed in the workspace once the robot topologies are selected, Fig. 7.13. Tasks are basically described in terms of activity modes, plotting the path and the attitude of the end-effector. The requirement is investigated solving the backward-kinematics problem (referred to trajectory planners), to plot the mobilities (or joints co-ordinates) trends. The solutions, referred to six-degrees-of-freedom robots, can present singularities and the selection of the correct branching needs complex tests when numerical procedures are implemented.

The hindrance is removed by the SIRI-CA framework: with resort to the operation constraints, that characterize actual manipulators, a set of modular elements are chosen; and then, restricting the study to six mobilities configurations, expressed by sequences of sliding or revolving joints, analytical solutions are worked out [ACM86]. The SIRI-CA framework contains a library for generating task-consistent sequences of activity modes, (i.e., three mobilities are basically employed for covering the work volume and three for the local position trimming and the attitude setting). The availability of analytical formats for workspace to joint space mapping provides a direct check on the robot congruence with regard to both the fixed and moving obstacles in the task domain.

- *Dynamic nonlinearities analysis*—Factory automation, with the increased versatility of the resources, moves toward high performance (in speed and accuracy) fixtures. Their dynamics should be generated, fully describing the inertial crosscoupling effects, to quantify the actual properties [ACM96d]. With heavy pay-loads, member compliance effects should be considered [AMP89], [Kov97]. Several programming facilities already exist. The package SIRI-AD was originally developed by the authors and employed as a service kernel of the simulation environment [AMM84b], modularly built for the development of robotic equipment. It can be expanded to cover different actuation possibilities.

This package is based on the recurrent modeling of the dynamics of the supported rigid bodies going back from the distal member to the fixed base. A preprocessing block (incorporating a 3-D geometric modeler) for shaping the robot arms and computing the related structural parameters (center of gravity positions, bulk quadratic moments, etc.) is included. The user can display the robot topology and check the configurations, all along any given task, each time calling on the graphic routines for visual presentations. The dynamics depends on the actuation laws and the solutions are available in the joint space and in the work-space. Referring to the development stages of Fig 7.2, the SIRI-AD framework provides the pertinent data for setting the actuators, once a reference configuration is obtained with the help of the SIRI-CA package.

- *Steering strategies analysis*—Robot design, (Fig. 7.11), needs the phases of selecting the control strategies; of verifying the task-congruence effectiveness; and of integrating the equipment in the manufacturing process. The availability of high efficiency processing devices enables families of feasible strategies with comparatively high sophistication-level control-schemes. Dynamic nonlinearities can be accounted for if the appropriate simulation facilities are employed starting with the ideation phase.

The SIRI-SC framework is, accordingly, built as standard CAD reference with modular layout; it can be extended to include all the different control options in use or proposed [ACM93], Fig. 7.14, such as,

- Point-to-point and path-continuous control with kinetically-balanced feedback;
- Position-follower control with force feedback and partial kinematics compensation;
- Piece-wise control with local (numerical) inversion of the (full) dynamics equations;
- Global compensation control by uncoupling of dynamical nonlinearities interactions;
- Adaptive (model referenced) optimal control with weighted rms performance index;
- Statistical observer control with parametric (fading memory) trajectory estimator;
- Probabilistic observer control with a stochastic (Gauss-Markov) dynamics modeler.

The global compensation control is a very efficient option, bringing higher performance with some computational burden; however, practical implementations are still lacking, in reason, mainly of the

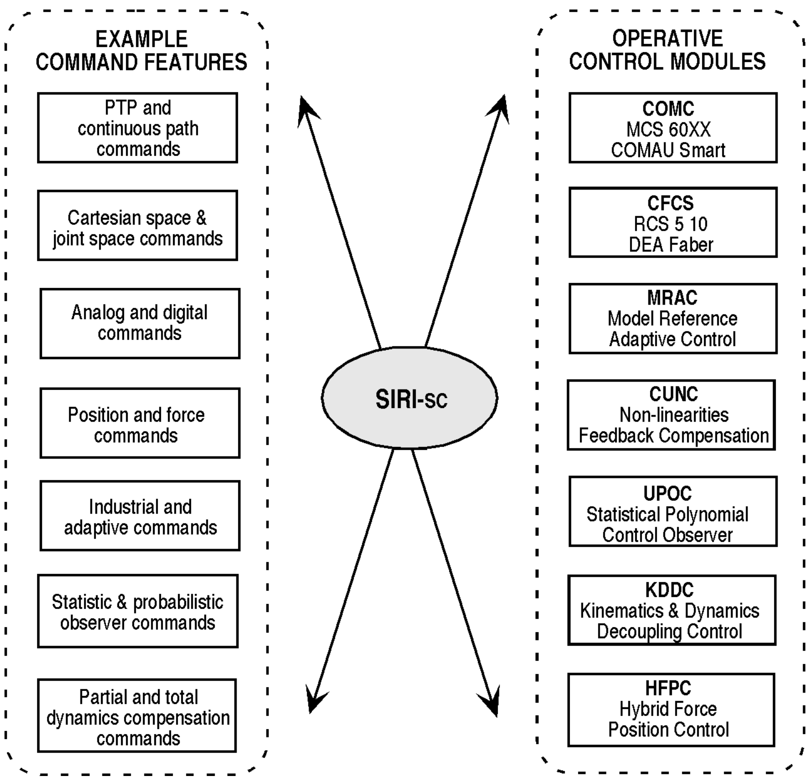

FIGURE 7.14 Features of the SIRI-SC framework.

restricted familiarity with the stability of motion of nonlinear systems. The reference to approximated models having the compensation limited to backward kinematics transforms [MPM78] is considered for the cases liable to simple use. The adaptive optimal control [AMM84a] deserves special interest for theoretic studies. The results have "robustness" limitations and generally present computation problems. The inclusion of observers with the function of (multi-variable) feed-forward compensators, is also useful. A good bargain between performance and complexity is obtained with polynomial fading-memory filtering [BMM85]. The control strategy based on the numerical inversion of the dynamics equations [Whi69a], [AMM87] is finally included in the SIRI-SC library to be employed to generate the reference trajectories for the performance estimation of the different control strategies.

The ability of changing the manipulator dynamics, by setting a command law that depends on the running behaviour, can be used to force the motion according to given requirements. Dynamics "shaping," for instance, allows the uncoupling of each joint as linear (second order) block provided that the appropriate compensation is applied. The result can be obtained by acceleration data and feedback closure or by model-based feed-forward modulation. When both options exist, the self-calibration is simply performed along with unconstrained tasks.

Specialized Options of the CAD Environment

The simulation environment SIRIxx has purposely been developed for assessing, with reliableness, the robot accuracy, dexterity, efficiency, and versatility figures. The environment has been expanded, on a modular base, for dressing the analysis abilities for innovatory robotics, into standard evaluation frames. In order to achieve additional or particular properties, as required for most advanced applications, a second group of packages has been developed aiming at more detailed goals. Example packages are:

- SIRI-AT: providing the animation of the tasks progression possibly interfaced to time-varying surroundings [CMP94]; the graphic restitution is based on standard softwares.
- SIRI-UM: showing the consequences of elastic and anelastic impacts of the end-effectors against fixed or moving obstacles [ACM96a]. Impulses are propagated along the members to the joints and the related actuators.
- SIRI-HD: generating combined position/force feed-backs, interfaced with structured or unstructured surroundings [ACC93], where redundancy improves accuracy and versatility.
- SIRI-MR: assessing the options of multi-robot equipment with co-ordination to enable recurrent job refinement [ACM91a, AMM91c]; cooperation improves dexterity and efficiency.

The list is recalled to show how diversified subjects arise during actual design cycles. As before, short comments on the typical situations faced by a designer are given.

- *Operation details analysis*—The visual restitution by means of the SIRI-AT animation is a powerful aid for robot path planning including obstacles avoidance checks. At a higher level of complexity, the assessment of the collision effects is provided by the SIRI-UM package [ACC94a]. The technical literature on the subject leaves more questions open than solved. The impacts of robot members (against rigid or compliant bodies) are usually non-central with reflected effects on both normal and tangential rebounding speed components. Fully consistent analyses do not exist (unless for the single-degree-of-freedom case) and they could lead to unnecessary complexity models since practical situations do not require control of the collision behavior but rather only to avoid unacceptable fall-offs. Then, with SIRI-UM, a simplified analysis is provided based on the introduction of suitable bouncing coefficients which supply a consistent restitution of the impact, correctly complying with energy decay and momentum balance requirements.

The analysis of details is quite often neglected, since the activity modes selected for the progression of the requested tasks should avoid the pitfall of even approaching the related risks. High performance robots, in any case, must compensate discontinuities at the engagement phase, when the unconstrained navigation phase stops giving place to the constrained work phase. The region could characterize collision effects with rebounding and bouncing phenomena, [ACC94b]. The resort to simplified identification procedures to support appropriate task setting operations looks promising, by-passing the theoretical and practical difficulties of fully developed models. Duly assessed system hypotheses help the self-calibration of the codes, to fit continuity link-up.

- *Task extension analysis*—Functional redundancy is a basic option in advanced robotics. The related technical literature is large with several suggestions [AsA88], [AsH89], [AsY89], [Ben97], [ACH86b], [AaH77], [ESG90], [KiT97], [LiY97], [Sim75]. The command redundancy is a simple option with different implementations [AMM91a], [AsI89], [CPP96], [Des96], [FFM97], [MHS97], [Pel96], [RaC85], [Whi87], [WLY96a], [YLI96]. It is studied by the SIRI-HD package by combining force and position feedbacks. Mobility redundancy is a more complex option, with several fall-offs [HuJ86], [KAG96a], [LII96], [LiA92], [MiI96], [NoH89], [UIH97], [YoZ93], [ZLY87]. It is tackled with the SIRI-MR package introducing the combined cooperation of multiple-robot fixtures. Example developments are discussed in the following paragraphs and hints are given as introductory remarks and for the re-design operations based on process-matching requests.

The ability of separately closing position force controls can be used for driving the robot to follow a trajectory, transmitting a pre-set effort law. During the work phases of the robot, independent sensing devices provide useful data for closing the appropriate feedback loops. When state expansion makes it possible to model the interfacing context, the dependence of force data and position data requires fading away of the redundancy (suppressing over-specification). Processing of the extra information is for calibration purposes.

The attribution of operation redundancy is a design trick to comply within robotics when the requested functions are not easily faced by the usual six mobilities. Addition of freedom to a single arm has anthropomorphic justifications and is a good contrivance when the end-effector, for instance, operates within a bounded work space previously reached through a narrow entry. Trajectory and control plannings usually split into sub-tasks: the approaching (or latching) and the operation (or tracking) tasks. More general setups based on multi-robot equipment with cooperation deserve special attention (Fig. 7.15). Situations leading to such directions are quite different, thus, a general purpose simulation environment is a very important design aid usefully explained with case applications.

7.3 The Design of Process-Attuned Robots

The study of specialized options, generally, profits the systematic approach built by using the general purposes-modules of SIRIxx and recording the results into the data-base of the SIRI-XE package. Still, detailed developments sometimes, require further studies when the individual applications concern, for example, subtle details or broad duty areas. In the former instances, accurate modeling of tasks progression

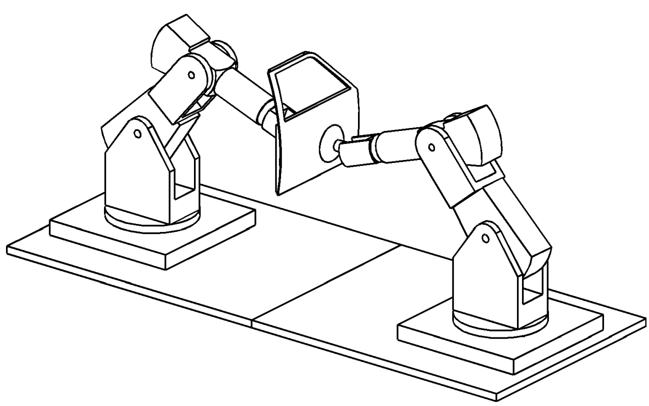

FIGURE 7.15 Robots with cooperation setup.

might result in difficulty, critically effecting the recognition of negligible effects on task planning. In the latter instances, consistent identification of unique robot setups could fail unless relevant refixturing or retro-fitting are performed to accomplish each sub-set of tasks. Operation peculiarities and job capabilities are both easily assessed when the design of the "new" fixtures follows a modularly-constrained development track.

Emphasis on modularity to expand robot's permitted activity modes has to be faced at both the CFC and the MDM frame levels. The philosophy that lies behind "earlier" robotics was that hardware fixtures should have been capable of being adapted by merely reprogramming. Selection of equipment that will best suit the needs of flexible automation is, however, a more difficult and costly exercise. The goal is simplified by joining the use of proper CAD supports (e.g., SIRIxx) with the standardization of the reference units and functions as well, so that the appropriate set-ups and fit-outs would effect outcome by combining a series of modules. The specification of the suited solution is alleviated by the previously performed analysis procedure on the standard units and functions and the synthesis procedure follows, (Fig. 7.16), according to the rule: "to determine the appropriate CFC frame, by joining the set of modules (functions and units) with the proper MDM frame, enabling the set of useful tasks with performance explicitly weighed by process specialisation." On these grounds, modularity is exploited as conditional aid of the ideation stages, (Fig. 7.2), indeed, the architecture setting has task-driven global bounds which specialize any given acceptable topology—the governing fitting has performance-driven approval tests to verify innovation appropriateness.

This "global" design cycle exploits modularity for a two-fold choice orientation:

- General purposes kinematics modeling techniques, control strategies assessments, etc., provide the classification rules for acknowledging the functional units consistency in relation to the process and for comparing their appropriateness to perform the tasks.
- Technical data, specially attributed to each unit, immediately provides the mechanical design parameters of the proposed solution (geometry, center of mass, weight, mass quadratic moments, joint stiffness, velocity/acceleration/torque limits, etc.) to help identify the expected performance figures.

Three of the four steps of the design-cycle procedure, (Fig. 7.1), are accomplished transferring the properties of the units with "global" consistency assessments. The fourth step leads to reconsidering the duty figures as actual achievements, readily starting the re-design activity with focus on the actual process where robots are introduced. The results of each new design-cycle procedure are background knowledge to start the process back-poised design of specialized equipment; in particular, by means of the already mentioned SIRI-XE package. They are stored, (Fig. 7.13), into a properly ordered database. Innovation is built step after step, acknowledging the "task requirements—functional blocks" pairs in terms of weighed performance indices (technical figures 'accuracy, dexterity, efficiency, and versatility' and economical return on investment). The designer makes inquiries from background knowledge that he can

Hardware modules adaptation (CFC frame)	
***C**omponent,* ***F**acility-configuration, and* ***C**ommand* *frame*	The manipulation setup is specified as feasible topology granting the given tasks, by means of a 'global' design cycle defined by a series of transform matrices, through whom joint axes architecture, links length, mobilities spans, actuation ranges, etc., are provided.
Software modules adaptation (MDM frame)	
***M**onitoring,* ***D**ecision-manifold, and* ***M**anagement* *frame*	The functional fit-out is specified as an activity model which accomplishes the tasks with the current topology; the activities are described by the effector position and attitude in the work-space, the tip velocity/acceleration, the allowable arm deflection, the transmitted force/torque, etc.

FIGURE 7.16 Synthesis of process-attuned modular equipment.

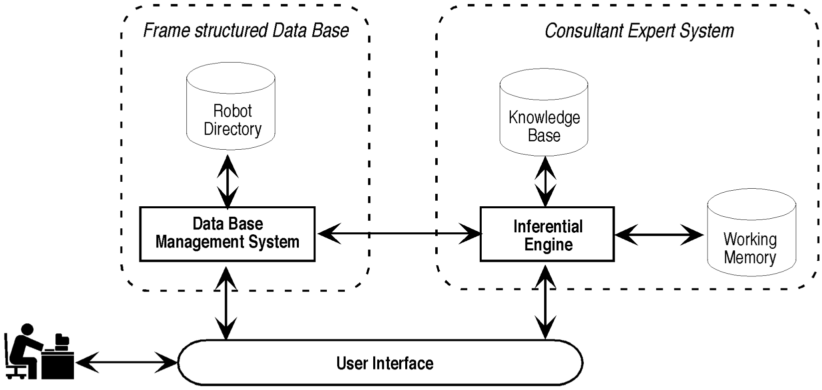

FIGURE 7.17 Decision cycle supported by the SIRI-XE package.

extract from overall formalized solutions when the process, to which the robot has to be linked, has already been studied. Most of the time, he will receive suggestions or only preliminary-by-default solutions. The logic of the SIRI-XE package, (Fig. 7.17), is built on sets of rule-based procedures that can be expanded or modified by the user to personalize, not only the reference knowledge, but the decisional patterns.

It should be noted that knowledge updating and maintenance of the expert system will become difficult to keep the reference background at satisfactory levels. Indeed, "industrial robotics" has reached the range of technological appropriateness and the number of equipment grants return-on-investment to manufacturers. In other fields, large opportunities like to be established as soon as the critical threshold of economic efficiency is achieved (this is expected to be, e.g., the case of micro-robotics).

Simultaneous Design of Robot-and-Process

The design of instrumental robots is strongly affected by the on-duty requirements concerning the facility and the related functional blocks. Actually, design does not end with the development (from conception, to construction) of the fixture. It should cover its life-long management including every action for programming and re-fixturing or for fitting and calibration. Indeed, the "quality" of the accomplished tasks and, indirectly, of the processed artifacts should be granted by restoring actions (pro-active planning), aimed at avoiding, extra costs of products approval tests and risk of regeneration jobs for the delivered services. Thereafter, return-on-investment in flexible automation is assessed by showing the advantages obtained by the setting the appropriate layout and fitting of proper governing logic. Among the advantages, process-granted "quality" is an inherent fall-out to be taken into account.

This discourse has been dealing with the design of instrumental robots, emphasizing the computer aids, prepared basically as CAD instruments for the development of the equipment for intelligent manufacturing. Industrial robots, in this context, are function-oriented equipment with duty adaptivity and 'intelligence' to that goal. For factory automation, robots have in-charge jobs (handling, inspection, assembly, etc.) required to enable unmanned running operations, in time-varying production plans and product mixes. Robotics is, thus, the reference technology for intelligent manufacturing, as opposed to fixed automation; the functional orientation is the basic design reference to comply with versatility (while productivity lays behind). Due to the variability of the production process, the action modes are large in number and tightly cross-coupled; then, computer aids, and ideation phases are relevant for on-duty iterated use, to manage hardware and software resources, and to provide helpful assistance to fit up and refit, to trim and adapt, etc. the available facilities so that the actual situations are faced with the best preset capabilities.

The evaluation of the return on investment appears to be a complex business since effectiveness has to be enabled along the operation life of the robot. Best performance, in fact, is achieved step by step on the condition that transparent knowledge processing is done during the robot life-cycle, from the conception along the running phases to the final breaking up, in order to make it possible

- to simulate the actual robot dynamical behavior aiming at virtual reality checks;
- to perform data fusion, with measurement restitution steered by system hypotheses;
- to promote command options, depending on control/mobility redundancies;
- to explore operation alternatives, suggested and assessed by expert modules.

Robotics is a multi-disciplinary area, obtained by merging many technologies to work out "mechatronics" issues through the cooperative effort of experts in several fields. Cooperative knowledge processing means that scientifically consistent bounds are established between engineers which concurrently work toward the solution with participated responsiveness. Experts may operate independently (at their own concern), putting in common requests and results and sharing the over-all reference knowledge. Final robots possess properties selected through the collaboration (with contribution, from designers and users), on condition that a unifying CAD environment is accessed *simultaneously* by all involved people.

This is the main idea of simultaneous engineering, with side off-springs such as

- integrating application studies with research seductive option with fruitful issues; and
- economic considerations cannot be separated from technical specifications, but need to be assessed with care, to help rank design alternatives in terms of process requests.

The criteria can be used to build an expert system, which helps to recognize good from bad fixtures. The job cannot be accomplished unless manufacturing engineers are asked to cooperate, so that no single issue dominates. The cooperation presumes structured knowledge environments and, possibly, modularly-arranged processing aids. From the collaborative effort, robots might be modified by removing or simplifying functions to agree with process fundamentals. With re-engineering, moreover, product-and-process may be changed as well, as technology-driven solutions are revised.

The Robot Setting: Equipment Modularity

In flexible automation, the main emphasis is reserved to "programmability." Robots are developed to be able to adapt themselves to any new product or process merely by reprogramming. The issue depends on (Fig. 7.18) the combined accuracy, dexterity, flexibility, and versatility figures needed by the manufacturing strategies: "versatility" means how far the task domain extends; "flexibility" specifies the on-process adaptability range; "dexterity" measures the duty level of complexity; and "accuracy" specifies the metrologic criticality of each operation. These are technical requests to be weighed against "productivity" for manufacturing applications. Robots, of course, never reach the productivity of special purpose devices used in fixed automation. Yet, single-purpose resources become useless when artifacts to be processed are modified. To preserve high productivity, while making it possible to recover the resources for different productions, 'modular robots' could be the right solution. The implementations are a typical issue of simultaneous engineering as standardization presumes the combined knowledge of robotics and the process-and-product design; the technical literature [BZL89], [CLC92], [GKY84], [HWM86], [Kan83], [KeK88], [LeR87], [MuM84], [ShS84], [SmC82], [TeB89], [Wur86] provides several useful indications.

A modular robot consists of standard units (links, joints, auxiliary rigs, etc.) which may be configured into suited arms as soon as new tasks are defined. This authorizes the exploitation of oriented devices (e.g., arms with only one or two mobilities) each time this is consistent with a given manufacturing process. Versatility is fully fixed off-process while flexibility is compressed as low as possible. The productivity can rise considerably on the current tactical horizons, due to the final fixture specialization. The stops, to implement the "new" robots of each new production program, are an unavoidable drawback to be removed

accuracy	quality obtained by combining repeatability (range of random spreads) and unbiaseness (range of systematic off-sets)
dexterity	specified in terms of tasks complexity with the related specifications on path planning and on control modulation requirements
efficiency	established by the swiftness of successfully accomplished work-cycles, with inclusion of set-up time and temptative trials
flexibility	range of the functional capabilities which assure the on-process adaptivity of the equipment for performing all the scheduled tasks
productivity	conventional measurement of the amount of items, produced according to standard schedules, over a given time span
versatility	domain of the reachable tasks, possibly, obtained, after re-fixturing and re-programming, to re-focus the robot functional orientation

FIGURE 7.18 Performance figures of instrumental robots.

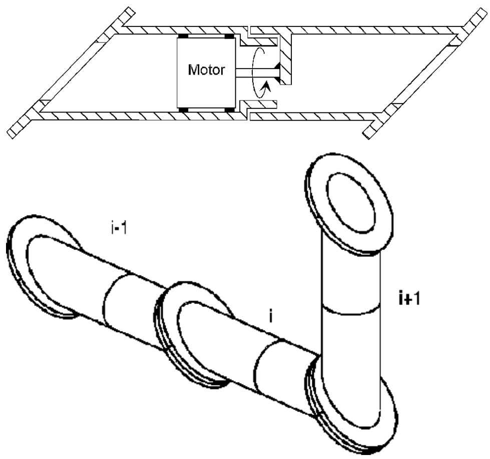

FIGURE 7.19 Example robot built with modular units.

by careful, simultaneous engineering (putting in parallel artefacts and production resources development) and standardizing previously arranged hardware and software units.

On the marketplace, (Fig. 7.19), the modular robots are offered with different levels of complexity. The assembly of small plastic artifacts, to be delivered by extended batches, is a sample case where the rig modularity has been explored to reach return on investment [ACM96e]. The development of the fixtures is, basically, concerned with an inventory of properly assorted units and by composition procedures based on pre-established patterns, such as

- Units are self-standing structures (links, joints, sensors, grippers, etc.).
- Each unit has self-contained function (e.g.: link with included actuator).
- Congruent units connect each other, through standard coupling.
- Auxiliary units (sensors, etc.) can be superposed, regardless of size, type, etc.
- Individual unit has optimized design, in terms of a selected set of charges.
- Reference setups are available, with properly tested characteristics.
- Software modularity provides fit-out schemes, with known performance.
- Similar other prescriptions automatize the access to the inventory.

The conceptual design, then, is very effectively done with help of the basic packages of the SIRIxx environment.

- SIRI-CA supports path planning and architectural analysis to minimize the number of mobilities, frozen-joints models that are used to specify actual links and the architectures are analyzed with respect to only the task-driven paths.
- SIRI-SC assures control planning and performance analysis. The structural parameters are directly transferred from the inventory and the control strategies are programed for use on related processing units.

The modularization considered in this paragraph establishes constraints mainly on the mechanical side of robotics. Sensing and computer units are already available as standard units; thus, no relevant limitation is expected. Now, robots are dextrous devices charged to accomplish, with autonomy, given tasks; being allowed to use their *intelligence* of the world they are interacting with according to this definition, the modular fixtures happen to be classified as 'robots,' depending on the amount of 'intelligence' they are using, properly equipped for on-process duties. Overall flexibility is, in any case, the winning option to working out the appropriate setup by the off-line investigation and to transfer the efficient supervision at the level of on-line operativity. In summary, the design of process-attuned robots, by integrating series of properly standardized units, is aimed at timely equipment re-setting (CFC frame) while performing the overall re-engineering of product-and-process.

The Robot Fitting: Versatility by Process Back-Poising

Reference to standard units only is often too restrictive resulting in final configurations too complex or not properly balanced and, in general, poorly optimized. A different kind of modularity has been discussed in the chapter based on the idea of process back-poised standardization. At this stage, the innovation could bring unsuspected options and few hints are given. Instrumental robots are operation-oriented devices with programmable functions related to allocated tasks and adaptivity depending on the autonomy latitude and performance ranges. Their development requires the previous acknowledgement of the on-duty behavior to be established within actual operation conditions with model-based computer simulation (starting at earlier conceptualization, during the design steps, and covering the life-long task programming to manage the on-duty fitting). The process-attuned standardization simply means to fix a set of procedures (rules or algorithms) in order to systematically combine the "activity modes" (of production agendas) and the "equipment set-ups" (of processing resources).

Then, upgrading in instrumental robotics is explored by mapping functions (MDM frame) into equipments (CFC frame) which share, as a standard feature, the knowledge of the tasks to be performed. Once the resources are detailed, the planning is the critical request and the effectiveness endowment is dramatically dependent on the capability (based on system hypotheses) of continuously assessing the task progression, aiming at adapting the operation sequences in such a way that disturbances are filtered and offsetting influences are avoided. The issue is reached (Fig. 7.20) by exploiting dated process information and the conditioning relational contexts and is based on

- The availability of models with manipulation dynamics so that robot behavior is predicted with the requested approximation;
- The inclusion of standard sensing devices, to provide directly or indirectly, visibility on every quantity which may affect robot performance;
- The ranking of the feasible redundant setups in order to supply control fits in and/or mobility options for higher robot effectiveness;
- The access to common decision aids with incorporated 'expertise' to simplify the robot setup and to improve its operation efficiency.

With process-attuned standards, an instrumental equipment is directly related to the tasks and, in a moderate manner, affected by methods or procedures that man has discovered to obtain, results. This becomes the starting point to innovation. Actually, robot potentialities are considered more and more to supply effective solutions to the many manipulation tasks that actually are out of man's possibilities.

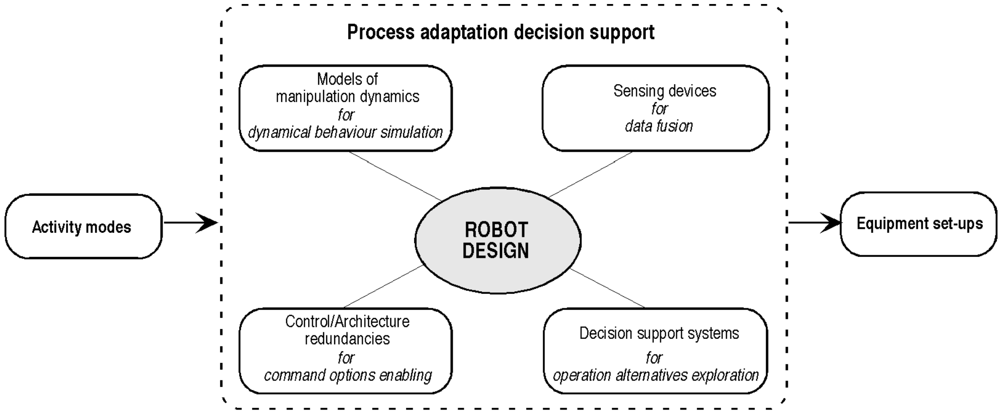

FIGURE 7.20 Basic requirements for robot's design effectiveness.

medical apparatus and services	prosthetic devices with constraints on weight, on articulation and function range, on mutual stability of operative sequences, etc.
surgical equipment	catheter-based micro-manipulators for repairing blood vessels, automatic micro-lancets for remote operations, etc.
instruments for scientific research	micro-actuators for force-balance sensors, micro-optical benches, micro-handling of biological materials, etc.
manufacturing equipment	components for aligning and assembly of optical fibers, active probes for micro-electronic applications, etc.
clean room instrumentation	the down-sizing reduces costs of keeping the production facilities of drug and biochemical industries, etc. free of particulate.
advanced consumer products	printer mechanisms made smaller, micro-sized servo actuators with multiple force-path constraints, etc.

FIGURE 7.21 Example applications in micro-robotics.

Between the new fields of instrumental robotics, the area of *micro-dynamical systems*, for instance, deserves attention and several example applications, (Fig. 7.21), already cover specialized market areas. These new applications of instrumental robotics are characterized by the need of exploiting to the highest degree the amount of information available, since the success critically depends on the ability of acknowledging the task progression with continuity. This acknowledgement is based on the availability of appropriate models of the controlled manipulation dynamics; extended (direct or indirect) visibility on the process variables; and convenient redundancy of the controlling capabilities. In other words, we seek a robot with versatility capable of being properly balanced to the process requirements. As a particular instance, micro-robotics is recognized as requiring sophisticated model-based computer-simulators, observers-driven sensors-data fusion, and dynamics-shaping control capabilities. These research efforts are, however, common trends for instrumental robotics, for developing specialized and effective devices with the low-cost desirability which assures market rentability.

The equipment resetting and retro-fitting are accomplishments that introduce the shift from a "special" technology, such as *robotics*, to a broader engineering context, namely, the *design activity.* At the end of the evolution, robots might not preserve a technological independence any more (adding multi-disciplinary knowledge); by now, innovation is issued with aids which help solve an engineering design problem. Micro-robotics has been used to exemplify the trend: designers look at "on-duty" (process-attuned) prerequisites as a principal concern of a re-engineering business; not as advanced achievement of robot technology.

Robot Dynamics with Constrained Motion Duties

Aimed at process tuning, the robot's manueuvers will principally be concerned with constrained motion models, (Fig. 7.8). In Section 7·2, the connection between a robot and the environment has already been given by means of the "impedance" G(s); binding the incremental deviation of the coupling force (and torque) δF_E with the position (and attitude) infinitesimal off-sets of the end-effector from the equilibrium location, the linearized model follows:

$$\delta\tilde{F}_E = G(s)\delta\tilde{x} \quad \text{with: } G(s) = Ms^2 + Hs + K \qquad \text{(repeated)} \quad (7.7)$$

When the coupled work path starts, the model (7.4) describing the dynamical behaviour of the robot can be linearized to become:

$$\delta Q_A = A_q^*\delta\ddot{q} + B_q^*\delta q + D_q^*\delta\dot{q} + J^T\delta F_E \qquad (7.8)$$

where δQ_A is the incremental actuation torque; the A_q^* (reduced inertial terms); the B_q^* (reduced stiffness) heavily depend on the configuration, the reduced damping D_q^* is less sensitive, and the gyroscopic term, $D(q, \dot{q})$, since the second order in $\dot{q}$ becomes negligible after linearization.

To reduce off-set errors, the industrial robot controllers resort to joint commands (7.5) with, possibly, an integrative term,

$$\delta Q_m = E_1\int(q_\mathrm{d} - q)\mathrm{dt} + E_p(q_\mathrm{d} - q) - E_v(q_\mathrm{d} - q) \qquad (7.9)$$

δQ_m computed at the joint axes (the desired acceleration may not appear, being seldom available). Therefore, if the behavior of each actuator is approximated inside the motors linear range (before saturation), by the "equivalent" inertia and damping terms:

$$\delta Q_m - (\eta^2 J_m\ddot{q} + \eta^2 h_m\dot{q}) = \delta Q_A \qquad (7.10)$$

(where η is the matrix of gear ratios from motors to joint axes), then the closed loop dynamics is stated, with respect to the linear approximation (7.8), provided that the external inputs δx or δF_E and the actuation commands δQ_A are bounded both in magnitude and in frequency.

The effectiveness of instrumental robots by process-data acknowledgement shall not divert attention from their inborn faculties, namely, the behavioral adaptivity. This, rather than abstract qualification, corresponds to the ability of figuring out the dynamics by means of models by granting quantitative prediction of the motion. The aspects are considered to suggest a patterned approach for feeding in the process "knowledge" (possibly, by modularly arranged CAD supports) and to introduce concepts quite general in respect to the example applications of the following sections. In fact, a model remains a representation of the actual behavior for a certain duty range. The deviation is called the model (structural) uncertainty and the interlacing between deep knowledge frames (e.g., the above stated equations (7.7)–(7.10)) and shallow knowledge links (e.g., the rules of qualitative reasoning) should be explored to reduce this uncertainty [MCR96].

According to the said goal, the show of useful process data is enabled, recognized, and exploited, during the duty progression, mainly, for two reasons:

- For instrumental robots, as outcome of task departure monitoring; and
- For autonomous robots, as instance of task-planning success/failure.

In the first case, robot effectiveness is improved by means of the recalled options, (e.g., dynamics shaping to compensate the inertial coupling between joints) and redundant control (to have independent modulation of the effector position and force). In the second case, the availability of structured knowledge frames of the arm behavior can help modify task-planning, with relevant advantages for highly sensorized devices.

The concept of dynamics shaping has been defined as the capability of modifying the steering planning by combined adaptive feedbacks [Yos93]. The compensation of the reflected inertia dynamical coupling is quite an obvious modulation to counteract the internally generated inertia load. Up-grading is apparent for rigid arms required to track high speed navigation paths. Moving to the robot back-loads generated by external couplings, earlier studies, before any snags due to limited stiffness, considered strategies based on separate loops for position or force commands. The extension is justified by considering how redundancy is used by people to preserve the stability of motion, e.g., during everyday walking, or for expanding dexterity and versatility, for complex exercises. The model-based connection of force and position feedbacks is a primary goal for development in robotics. Most of the recalled micro-manipulation tasks, (Fig. 7.21), needing the graduation of the impressed force jointly with the effector displacement steering, require control redundancy. In fact, due to dynamics nonlinearity, any changes of accuracy or efficiency figures will also require task-driven adjustments, making control planning necessary in addition to path planning. Simple example developments are discussed in Section 7.4, for explanatory purposes.

One question is, moreover, the fact that robots could be required to operate with totally or partially unstructured constraints. As a general rule, the request is faced by "intelligence" of the outside world mastered by learning schemes to expand the range of successful duties. The practical evaluation of the effectiveness figures of abstractly defined duty ranges, however, worsen due to the arbitrariness of the reference standards and to difficulties of establishing consistent gauges. Instrumental robotics of recent years has preferred the gathering of "intelligence" of the outside world expanding experimental information and profitably doing data-fusion by combining sensor measurements and system hypotheses; whereas autonomous robots may struggle against vagueness another way, by learning cycles built, e.g., on qualitative reasoning. Computer aids, with knowledge frames similarly based on the said four logic steps, (Fig. 7.1), can be used for exploring the feasibility of prospective tasks when open-duty activity modes are addressed for goal-oriented planning performed into unknown surroundings and unpredictable disturbances. Steering self-adaptability, learning ability, and recovery options are evaluated by fully autonomous agents with virtual reality experiments, supplying a rival show of closed-duty applications of the fixed automation. Iteration of functional design cycles, then, operatively provides a decision pattern for training procedures, granting self-learning abilities.

The integration of on-line measurements is the last, but not the least, of the problems related to process-tuning. Sensing devices are extensively used to measure internal coordinates e.g., encoders for joint angles. The addition of angular accelerometers makes it possible to obtain signals for the compensation, as shown in Fig. 7.7, of the nonlinear inertial couplings during the unconstrained navigation phases. Image analysis and optical scanning are useful means to derive surveillance functions for presetting the engagement phases; sensing devices at end-effector or wrist provide data for tactile recognition and hectic reactions and the incorporation into system knowledge profits by identifying a structured relationship of interactions at the robot/surroundings interface. Availability of reliable, low-cost devices supports the trend [ArM83], [FLG97], [DeS98], [HiH83], [Hil85], [LiG93], [RoM66], toward inclusion of new measurements. Quality and effectiveness require accurate calibration procedures and the related cost and time should be compressed and accounted for. The answer is "intelligent instrumentation," having standard self-calibration capabilities. The robot is specified through model-based control accounting for actual nonlinear dynamics; and, to conclude calibration, is endowed by a duly modeled interface. The data, collected by specified duty sequences, are processed and compared with "virtual" measurements for automatic calibration of the sensing and restitution devices.

The discussion on the on-process opportunities for expanding current information by means of learning capabilities and artificial reasoning or of measurement devices and data fusion, however, should not divert attention from pertinent models, such as the one represented by the Eqs. (7.7) through (7.10), which help describe the manipulator dynamics within given application ranges. This assumes a "nearly" valid prediction of the process evolution to be compared with measurements to have an insight on whether external disturbances would superimpose.

A Challenging Option: Robots with Cooperation

Process conditioning pops up as brain wave and multi-robot systems for task parallelism appear as innovation aiming at better productivity and/or effectiveness. The subject has already been concerned in several studies and sample applications exist with loose cooperation figures between units. To assess these figures, the specification of the multi-functional framework is requested, explicitly defining the relational structures of the task/performance cross-dependence and for the job-flow/resources concurrence. The co-operation problem is stated, at this stage, as distinguishing control loops (closure of physical feedback) and decision schemes (closure of logic nets), and join the efficiency of the in-line command operation with the flexibility of the in-process adaptivity whenever requested by the application. For duty-specification, the aspects to investigate include:

- Functional description of the job to assess the advantages of robot cooperation.
- Executional constraints with specification of task programming requirements.
- Govern and information fit-out to select control and communication setup.

Schedule meshing analysis, (Fig. 7.22), is done at first, to recognise if duties are closely bounded, sequentially related, or mainly self-sufficient. Cooperation, in fact, increases plant productivity as robots share portions of the job and are able to perform a large variety of actions. Therefore, task complexity, (Fig. 7.23), is analyzed to set the handling architecture and to fix the govern level hierarchy, namely:

- Logic sequencing, at lower scheduler level, to comply with the nesting of (off-process specified) tasks "closed-duty" agendas, accomplishing in parallel independent actions, to improve productivity.
- Communicate synchronized coordination, at intermediate planner level, to obtain the task-coordination by means of "sync-duty" operations, respecting the sequentiality of actions with priority constraints.
- Decisional mechanisms activation, at upper controller level, for matching tasks and "open-duty" environment in order to fulfilled jobs actually requiring collaborative effort to grant reliable results.

A third issue, data sharing requests are considered, to be satisfied at

- Operation range: scheduling/sequencing; devising/planning; observing/controlling;
- Govern range: centralized (controller level) or decentralized (scheduler level) policy.

The design of efficient multi-robot equipment depends on the application. It can be viewed as the most satisfying setup between conflicting goals such as: duty flexibility vs. setting quickness; task versatility vs. plant productivity; and job autonomy vs. quality assurance. Due to the complexity of the contrasts, choice of solutions needs to be explored since conceptualization, (referring to actual running conditions to check functional and decisional options exactly in the duty specification frame of the particular case). To limit development costs, general purpose CAD packages are a convenient means. A number of alternatives can be explored by comparing charges and benefits and contrasting functional and decisional options with quantitative figures of the robots' performance.

Handling and governing structures are the central issue in developing the overall fixture. The first characterizes defining the functional components: end-effectors, joints, kinematic chains, actuators, sensors, etc., and needs to be adapted to the manipulation surroundings (i.e. workspace, job requests, tasks agenda, information interfaces, control operations, etc.). Dexterity and accuracy push toward integrated sensing/command blocks and hybrid position/force control loops for the arm-coordination. The study is, accordingly, carried on by appropriate functional models: first, for the preliminary command-setting and path-planning with simple kinematic models; then, with full dynamic models that should include a library of control strategies, for operation checking and performances evaluation. The governing structure, (Fig. 7.24), has to continuously adapt actions to current situations related to on-going

CLOSED-DUTY the agendas are carried out simply managing the job parallelism	
Several robots may operate in a given workspace, supervised by schedulers, with 'passive' constraints (for collision avoidance, etc.).	• the decisional schemes are moved off-process • the command logic is pre-set, with reference to the executional stages (ruled by a scheduler)
SYNC-DUTY the agendas are implemented exploiting appropriate functional sequencing	
The planners govern the robots, with 'active' constraints on the job to be performed in parallel and/or in sequence	• the operation characterization is detailed within the set of '*a priori*' system-hypotheses • the task co-ordination follows a logic, previously assigned by (fixed) procedural knowledge
OPEN-DUTY the agendas are built with procedural knowledge, shared by the decentralized control units	
The job progression is ruled by controllers that schedule, with embedded decisional aids, the operations concurrence, based on updated information on the actual state	• the functional characterization of robots is given, with the class of authorized tasks • the coordination is adapted with the on-process knowledge

FIGURE 7.22 Specification of the schedules by "duty modes."

MANDATORY TASK COOPERATION two or more robots, simultaneously or jointly, perform the job, with links on individual tasks such as	
joint operated tasks	- the robots are doing a part of or the total job, for the fulfillment of which coupled cooperation is required
simultaneous tasks	- the operations require more than one robot, e.g., one robot serves as a programmable fixture for other robots
CONCURRENT TASK COOPERATION two or more robots carry out, in parallel, portions of the same job, having independent charges such as	
joint parallel tasks	- the robots work together on different facets of the same job, decreasing the total cycle time
split parallel tasks	- the robot diverse capabilities are exploited for specialized operations, e.g.: positioning, precision assembly, etc.
OPTIONAL TASK COOPERATION any one of several robots can fulfill the job and only one is required since the cooperation is based on	
interchangeable tasks	- the responsibilities can dynamically be assigned among the robots and the job accomplishment is covered with failure backup

FIGURE 7.23 Cooperation classing by "task modes."

Structures of the decision logic	• *hierarchic information tree-structure*: the cooperation among the robots is assured by a centralized control, under an explicitly established supervisor • *parallel-distributed information network*: cooperation exists in a multi-agent cluster of units (sharing common interest data) interfaced through an intelligent layer
Modes of the decision support	• to fulfill pre-scheduled steady operations, after command decentralization • to perform job planning, resetting the programmed-mode conditions • to recover the on-line control of the multi-robot facility, at emergencies
Outputs of the govern module	• at the executional level, for enabling the operations of each individual robot • at the coordination level, for controlling the cooperation between robots • at the organizational level, for acknowledging the programmed tasks

FIGURE 7.24 Decision-and-govern modes of multi-robots.

job progression. The scheduler activates the tasks parallelism and, once verified, the planned job sequencing. The controller, congruent with flexible surroundings, requires full visibility of tasks progression to exploit the updated knowledge on current situations; to modify the state depending on the scheduled duties; and eventually, to adapt the robot behavior in relation to the situational changes. The context brings a hierarchic knowledge reference framework to distinguish the "external" from the "internal" structural conditions and to prepare solving procedures consistent with the acknowledged relational schemes.

The preparation of the activity modes can be separated from their execution by the tasks given to the individual arm and the trajectories (with the related motion-wait conditions). Job fulfillment is programmed (planner level) off-line and synchronisation only is enabled during implementation. To govern cooperating robots, thus, requires a communication structure between units assuring

- At the scheduler level, the monitoring of closed-duty agendas;
- At the planner level, the sequencing of sync-duty agendas;
- At the controller level, the coordination of open-duty agendas.

7.4 Modulated-Control Example Developments

Improvement of robot potential has been related to the ability of modulating the behavior to reach accuracy, dexterity, flexibility, and versatility so that the specified handling tasks (even out of man's capability) are performed. The challenge, characterized by the use of dynamics shaping and/or force modulation, to subdue unwanted effects on the manipulator behavior, is by adapting the control to the on-going duties. Dynamics shaping corresponds, in fact [Yos93], to compensate systematic offsets or drifts which may arise due to: actuation nonlinearities, mobilities inertial couplings, transmission compliance, actuation backlash, sensors' bias, or the like, using error signals, measured or computed with respect to pre-set dynamics, in the joint-frame. Conversely, aiming at the force modulation, typical studies [AnH89] have considered strategies based on two commands (position or force), conveniently switched to drive the arm as the duty is modified to constrained motion manueuvers. A simpler setting lies in the impedance control ([Dra77], [Sal80], [Hog80], [Hog81], [Hog85], [KKN95], [Mil96], [Pel96], [CaB97]) which enables a force feedback mapped from position data on the condition that the coupling stiffness matrices are known. Both approaches could be explored to supply task-orientation aimed at position and/or force combined control. This strategy is suggested by the observation of how the redundancy is exploited by (trained) living subjects to preserve stability of motion and to improve dexterity and versatility (even the running of a man on discontinuous ground requires multifarious adaptivity, to select a complex balance of position and force reactions and to carry on with a stable gait). The availability of redundant information enables sets of (hybrid) options for governing the robots to stick to the planned task, even when biasing effects arise.

The above considerations show that to enable control adaptation means, at least: redundancy, as far as actuation actions, and transparency, as far as dynamics effects. The redundancy is investigated by models properly extended to cover (with the robot dynamics) the effects of the surroundings. The visibility is assured either

1. By a state observer, generated according to the *a priori* knowledge of the process. This will generate the robot behavior by means of the model. The basic control strategies to uncouple the workspace errors for the actuation feedback requires explicit shaping of the dynamics as internal reference knowledge; or
2. By a self-sufficient observation scheme based on sensors and processing units. State coordinates (in the workspace and in the jointspace) are measured to assure tasks execution (in workspace) with up-dated commands (in jointspace) and proper control of both, tip position and transmitted force.

The two options can be exploited simultaneously, building combined solutions:

- The internal model is important for the on-line processing of the uncoupling feedback based, for instance, on the "computed" torque method; and
- The sensors provide further data, useful to adapt, via supervisory mode, in-progress schedules and co-ordination requirements.

To improve robot performance, the reflected loads shall be "accommodated" rather than resisted. Earlier studies aimed at compensating the effects in a non-conflicting way. The manueuvers are recognized by the way the position controls unconstrained motion degrees-of-freedom (force control for constrained motion). Example cases are further discussed to show the relevance of the control planning, with respect to more traditional approaches (confined at the stage-of-path planning, only); in particular, for situations that might lead to an erratic robot behaviour, suppressing wavering through errors compensation, and improving accuracy and dexterity without penalizing versatility and efficiency; namely,

- An example deals with inconsistencies of the control capabilities that could appear depending on the reflected-inertial dynamic coupling.
- The second, aiming at measurement robots gives hints to design a high performance device when handling effectiveness ought be joined with steady accuracy.
- The third introduces position/force control problems showing the coupled stiffness effects on the path planning repeatability.
- The last considers haptic manipulation using touch information to close position-and-force feedback to keep 'sufficient' stability margins to the robot motion while the tasks progress.

The Process-Adapted Control Planning Setup

Robots are non-linear mechanical systems. The handling dynamics shows undesirable behavior such as: joints cross-coupling due to the reflected inertial terms; driving misfits produced by backlash, stiction, saturation, etc.; vibrations and accuracy losses rising from lumped and distributed compliance; and so on. From the actuation stand, each motor has to drive a load which depends on varying mechanical parameters with modulating inertial, compliance, and damping couplings effects. The locally linearized model with inclusion of motor and transmission effects reduced to the robot joint axes combines Eqs. (7.8) and (7.10), to obtain:

$$\delta\tilde{Q}_m = [(\eta^2 J_m + A_q^*)s^2 + (\eta^2 h_m + D_q^*)s + (k_m^* + B_q^*)]\delta\tilde{q} + J^T\delta\tilde{F}_E \frac{1}{k_m^*} = \frac{1}{\eta^2 k_m} + \frac{1}{k_A} \tag{7.11}$$

where motors' effects are scaled by the gear ratio η and the reflected dynamics adds to give: $J_T^* = (\eta^2 J_m + A_q^*)$, equivalent inertia; $h_T^* = (\eta^2 h_m + D_q^*)$; equivalent damping; and $k_T^* = (k_m^* + B_q^*)$, equivalent stiffness. The terms A_q^* and B_q^*, as said, heavily depend on the configuration, but are somewhat equalized when high gear ratios are used.

The model approximation is apparent each time the architecture deviations are not negligible; the motion does not progress slowly and without impacts, and one of the following facts holds:

- The motors are not geared through a speed reducer, i.e., direct drive actuation is used;
- Quick changes are tracked in the joint space (the 'equivalent' parameters vary rapidly as no steady contribution dominates), even if the end-effector moves slowly;
- High accuracy is required for given tasks, such as at contact-transient for quick plough during assembly operations.

The back effects of the constrained motion appear in the work space and have to be transformed in the jointspace leading to:

$$\delta\tilde{Q}_m = [J_T^* s^2 + h_T^* s + k_T^*]\delta\tilde{q} + J^T G(s) J\delta\tilde{q} \qquad \text{since: } \delta\tilde{F}_E = G(s)\delta\tilde{x} = G(s)J\delta\tilde{q} \tag{7.12}$$

Then the closure of feedback loops by with the usual error signals (7.5) or (7.9). The real behavior differs from the model (12) due to the set of discrepancies, to be evaluated in the practice, resorting to harmonic describing functions. These are defined for fixed classes of bounded magnitude and frequency [GrM61]; thereafter, letting $K_q^F(j\omega; \cdot\ ;;\ )$ represent the true manipulator dynamics at the selected configuration and for a driving harmonic wave of given amplitude, Fig. 25, the local deviation is expressed by:

$$K_q^F(j\omega; \omega_j, \Delta\omega, \Delta\delta q) - \{(h_T^* j\omega + k_T^* - J_T^*\omega^2) + J^T G(j\omega) J\} = e_q^E(j\omega; \omega_j, \Delta\omega, \Delta\delta q) \tag{7.13}$$

which confines the identified model, with respect to the true open-loop behavior, into specified bounds, separately dealing with:

- Manipulation uncertainty which includes the local linearization of the dynamics and the additional non-linearities on gearing stiction and stiffness; and
- Operating uncertainty which corresponds to insufficient knowledge on the coupled impedance $G(j\omega) = [(K - \omega^2 M) + j\omega H]$ parametrization.

The closed-loop behavior, (7.5) or (7.9), deals with further non-linearities such as motor saturation, which can be modeled as open-loop gain reduction for each given frequencies band.

For developing high-performance robots, models shall be "nearly" valid within each considered operation range. In this practice, the designer is mainly concerned with the two-duty conditions: free motion

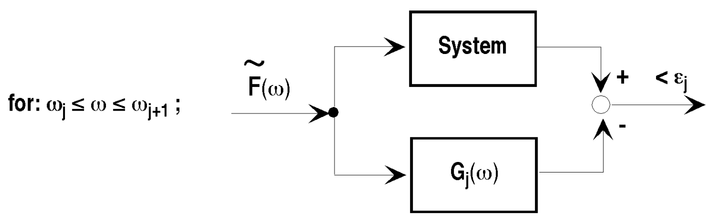

FIGURE 7.25 The identification rule for the set of describing models.

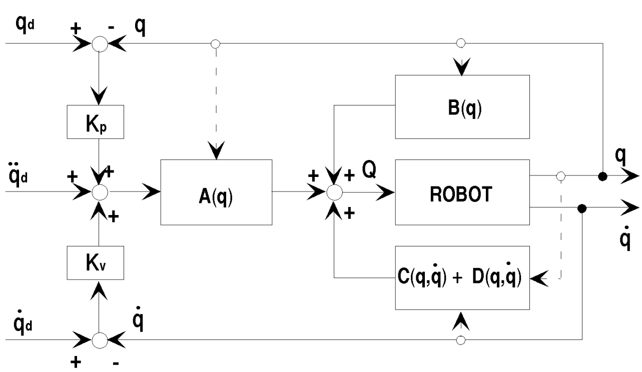

FIGURE 7.26 Computed-torque control.

and constrained motion. In any case, the relevance of the non-linear uncoupling and the perspectives (that *dynamics shaping* opens), are well explained by examples. The approaches proposed to figure out controls able to cope with the non-linear effects of the dynamics [ACM93], [AAC94] have as common an idea to change the actuation law in order to suppress the coupling so that the robot is forced to keep a linear behaviour while performing the assigned tasks. Coupled motion is, instead, controlled looking for "accommodation" attempts ruled by devising mechanical impedance figures in the frequency domain and by designing proper compensators by means of the (linearized) harmonic describing functions.

The effectiveness of the compensation strategy, with the first example, is proved looking at an existing robot: its dynamics is, first, verified by simulation with either the existing command or via the compensation, (Fig. 7.25), based on dynamics shaping aiming at fully suppressing the handling behavior inconsistencies by means of the "computed torque" method. The results show the usefulness of simulation for the transparent assessment of the task progression and for helping the control planning. The ability of expanding versatility and dexterity, moreover, is related to the possibility of including touch data on the end-effector path tracking. The exploitation of haptic artificial reality, however, cannot be effectively enabled, unless the composition laws of position and force data are related to the robot desired behavior, for performing the dynamics shaping. The basic comments are introduced by the second example.

Command Planning: Tip Wavering Under Inertial Coupling

The idea behind the "computed" torque method is that once gravity unbalances and transport terms are compensated, the forcing contribution Q^* related to the inertial coupling, should be superposed to cancel out undesirable effects and to assure that globally each robot mobility will behave as a perturbed double integrator with pre-established stability and robustness margin. Choice of the uncoupling compensation can be done by optimizing a performance index purposely defined for the set of the prescribed task paths (for improving steady efficiency), or according to general stability criteria in front of sharp disturbances (for a better transient behavior).

To consider this second option, Fig. 26, the following compensation:

$$Q_c = \Delta Q + Q^* = A(q)[E_p(q_d - q) + E_v(\dot{q}_d - \dot{q}) + \ddot{q}_d] + B(q) + C(q, \dot{q}) + D(q, \dot{q}) \tag{7.14}$$

will force the joint actuation, after uncoupling, to behave as a linear second-order block with critical damping. Downstream of the inertial compensation module, the model includes the additional nonlinearity due to motors' saturation. With higher gains, the control reacts promptly as long as joint motors remain in the proportional range (before saturation). This may reduce the loop safety margin, yielding to intolerable oscillations, unless the appropriate feed-forward compensation is computed, by modifying the command gains when the driving setting exceeds the saturation threshold. In such a case, the compensation of the reflected coupling inertial terms can only be approximated (at least for the individual feedback of the saturated joint actuator).

A quite instructive example problem was obtained during the investigations carried out with an industrial robot from a leading enterprise of the field. In order to reach a very accurate description of the robot actual dynamics, the setting of the centroids and of the mass quadratic moments of each individual member were obtained with a 3D solid modeler interfaced to the SIRIxx package. The original control modules provided by the robot manufacturer were analyzed and conveniently modeled. Then, simulation was carried out according to the testing procedures programmed with the standard operation prescriptions, in order to have the set of validation references for trimming of the SIRIxx code (see Fig. 7.27, for a typical test sheet), before carrying on comparative studies with more complex control strategies.

A particular trial is represented by the synchronous steering commands: a joint-interpolated trajectory is assigned between two points close to work-space boundaries, (Fig. 7.28), with the joint actuators that simultaneously start and stop and only exploit the convenient speed modulation for controlling the end-effector position and attitude. Even if the driving command settings do not exceed the saturation threshold of the motors, an undesirable wavering appears on the fifth joint of the robot (and of the model simulated with the original control setup). This causes current oscillations in the related motor, as can be seen in Fig. 7.29. The hindrance completely disappears when the compensation of the reflected inertial

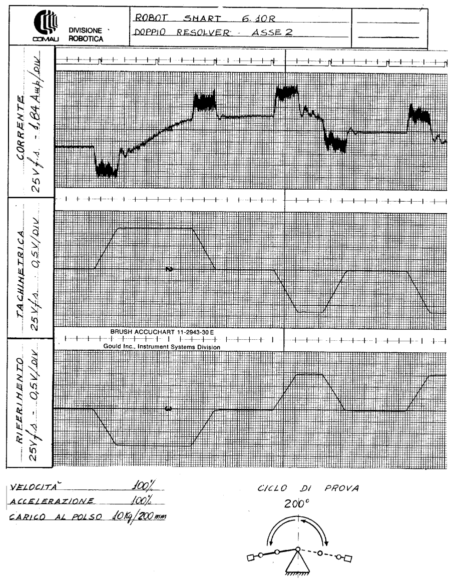

FIGURE 7.27 Test sheet for the simulation trial (courtesy COMAU).

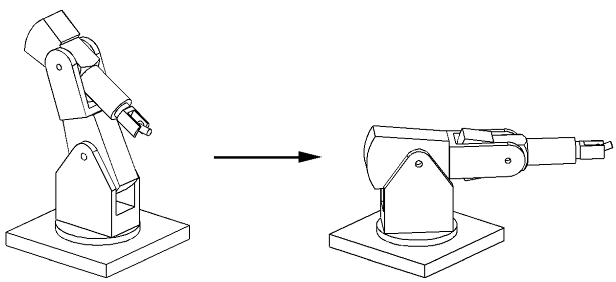

FIGURE 7.28 The synchronous steering commands test.

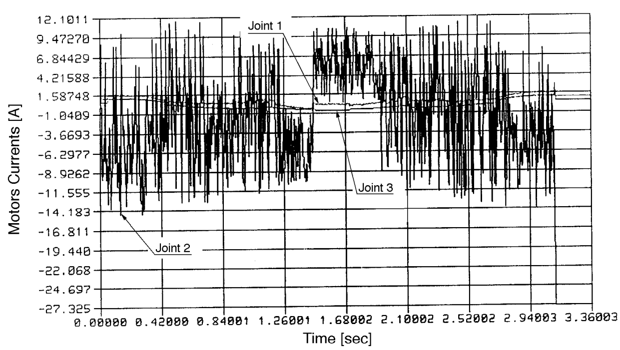

FIGURE 7.29 Disturbing effects of the non-linear reflected inertia couplings.

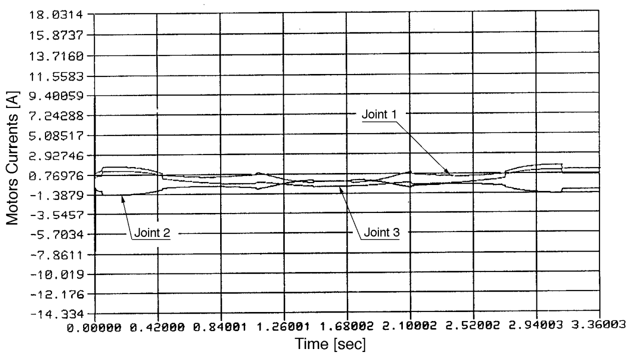

FIGURE 7.30 Manipulator's behavior with dynamics compensation control.

terms is introduced, (Fig. 7.30), in the model. The coupling dynamic modulation is very slight during usual operation tasks and is, in most of the cases, practically negligible on the end-effector when measured as out-of-all robot performance. The robot manufacturer was aware of this "anomalous" joint behaviour that could be avoided only by modifying the "admissible" task. Instead of looking at the inertial coupling effects, he was wondering about compliances in joint transmissions, aimed at increased stiffness without removing the dithering effects.

Explanatory evidence is easily reached by simulation once the robot behavior is modeled by means of a convenient code, (such as SIRIxx) making explicit reference to real architectures and contrasting the accuracy and dexterity limitations, and experimenting on facilities having a control strategy based on dynamics shaping. These kinds of results are, in the practice, quite often disregarded by robot manufacturers, as the "anomalies" appear (normally) for quite "pathological" manueuvers and are completely absent for rather extended duty ranges.

Measurement Robot Based on Controlled Laser Scanning

Measurement robots [CDM96] offer the cue for applications in control planning once the handling setups are properly selected. The form features restitution by contact or proximity sensors and needs free-motion high speed manueuvers and wide work-spaces. Laser scanning is a different option, assuring the detection of 3-D contours for remote shape recognition, with accuracy depending on the correct awareness of the sweeping path. In every situation, the balanced aims of low price and high performance require the careful design of the equipment to improve the effectiveness while keeping the mechanism to simplest dispositions. An example case is, for instance, the recognition of the cutting edge contour of tools to assess the wear-out degree and to verify the fitness-with purposes condition of on-going machining tasks. High contrast is mandatory and structured light is good by projecting light stripes onto the work surface or by layered illumination with laser beams. The design of the rig, accurately performing the mechanical scanning at high speed, shall certainly have to resort to uncoupling the actuation of each arm mobility. Then the fit of the sweeping path has to face abrupt swerves with reversal motors motion. The selection of the structural elements rizes according to critical changes. Hints about appropriate solutions are given hereafter, with purposely focused concern on the conception of a wrist with high manueuvers repeatability.

The measurement setting basically comprises the carrier of the optical beam source for back-lighting of the selected tool and the CCD camera. The image processor is run on a PC (by Speroni Power Vision software) to achieve contour resolution up to the requested detail level. Spacing and alignment are trimmed at fitting out of the carrying yoke; this shall approach sequentially the tools during their idle periods, properly fixing the position and the attitude of the yoke, to accomplish the complete analysis of the 3D cutting edge with reference to the given form features. The instrumented end-effector bears inherent complexity to allow setting and fitting operations; additional requisites concern its smooth driving, without quivers and jerks.

Some monitoring tasks are better performed by front illumination so an optional episcopic vision kit, with adjustable light intensity, can be used for the set of tasks that are properly carried out this way (Fig. 31). For that purpose, two cameras with different fields of vision can be used according to the present needs.

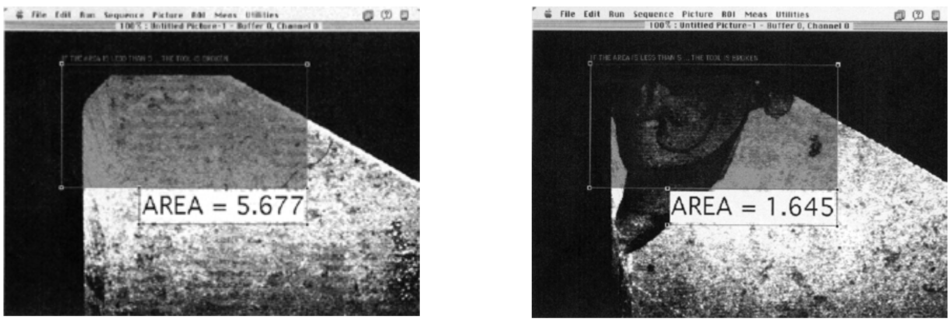

FIGURE 7.31 Shots of sound (a) and broken (b) tools illuminated by the episcopic vision kit. (Courtesy Speroni S.P.A.)

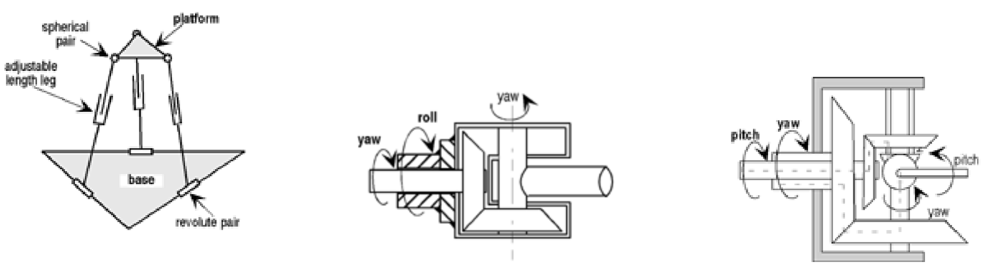

FIGURE 7.32 Concept solutions for alternative wrist settings.

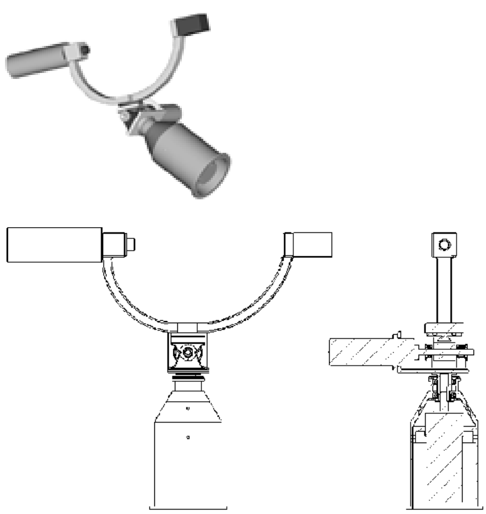

FIGURE 7.33 Assembly view (a) and design table (b) of the chosen wrist.

The appropriate equipment characterizes as a five-mobilities arm, with three links assuring the navigation path, ending with a high accuracy wrist. This needs the positioning assured in elevation of the sight line during arm-navigation. Then, a roll and yaw motion is performed to gather information on the cutting edge wear. Different concepts have been considered, (Fig. 7.32), including an in-parallel actuated arrangement [FaH97]; basic design specifications shall consider

- Backlash rejection to keep high accuracy during the laser beam scanning;
- Design compactness to increase dexterity and avoid impediments when carrying on data acquisition;
- Low weight to reduce dynamics back-effects during the work-cycle;
- Cost-effective design to increase product competitiveness.

The final solution, (Fig. 7.33), uses a direct drive of the roll and yaw axes, even if this implies higher loads to be carried by the roll motor and a bulkier structure. It seems to be the best solution, granting the requested high accuracy for camera's motion. Driving is realized by means of two AC brushless servomotors with harmonic drive reducers plus resolvers and holding brakes.

The solution, quite simple and composed of few parts, dramatically reduces backlash effects. The presence of a motor, directly mounted on the yaw axis, requires minimizing the masses to reduce the inertial coupling, while preserving high dexterity to the wrist motion. The development takes advantage from parametrical CAD tools for both the structural and dynamical analyses. The outcoming lay-out, to satisfy the functional requirements, brings to a set of technical features (such as: close together axes, rugged housing, camera nearby axes, etc.) that provide large stiffness and increase the driving efficiency, allowing high accuracy and repeatability. A simple PD controller is finally used, with the tuning of proportional and derivative gains obtained testing the robot (by extended simulation) during the execution of real operative tasks. This kinematical setting is uncoupled which makes it easier to design the control with the exception, of only a singularity at the center of the working space, when the roll axis is aligned with the yoke plate axis.

Modulated Command Options: Position/Force Feedback

Sometimes information redundancy is needed to perform complex tasks especially when the robot interacts with poorly structured surroundings or the task itself requires control of the contact forces (like: precision assembly, parts finishing, etc.). In these cases; *position/force* methods with distinct feedback loops might be used to be able to trim the value of the applied force *and* the attained position along the given axes of the (possibly) compliant engagement. The evaluation of the interaction force between robot and environment is sometimes directly measured and sometimes indirectly assessed with the *impedance control* that simply aims at monitoring the tip displacement and at making use of the contact path of the end-effector with the environment, to obtain the information.

The SIRI-HD package, [AMM91a], [ACC93], (as already pointed out in Fig. 7.9), has been based on the redundant control options, and independent feedback loops are closed for position-attitude and for force-torque errors. Joint rates are monitored while force rates can either be measured by a wrist sensor or deduced through a model of the coupling. The resulting control forcing terms F_c are finally transformed into the appropriate actuation signals as usual, by means of the transposed Jacobian matrix (7.6). In general, the control logic is switched by convenient $[S]$ and $[\bar{S}]$ matrices that select the combination of "position" or "force" commands separately for unconstrained or constrained maneuvers. The choice depends on the task progression. Compliance and dynamics of the manipulated object can be considered explicitly, during SIRI-HD programming. The overall scheme, finally, allows:

- The setting of joint-space commands for controlling the interfacing force;
- The closure of force loops by respect of sensors at the robot wrist;
- The closure of position loops by respect of sensors in the work space.

With the *impedance control*, when the tip is in contact with its environment and a new reference location is commanded, the resulting interactions are under control. The fixture accepts position-attitude set points and reflecting force-torque outputs which depend on the (assumed) interfacing impedance. The method easily applies to the usual position-controlled robots, reprogramming the feedback gains by means of the force mapped signals. On the contrary, the retrofit of position-control fixtures requires (costly) force sensors and the balancing of the two separate feedbacks on the transmitted force and on the tip location (with respect to an absolute reference frame). Many times, however, contact force control is sufficient to successfully accomplish manipulation tasks as the tip constrained motion provides path steering with "convenient" tolerances. These situations are, thus, consistent to the "computed" torque method on the condition, of course, that, throughout, checks based on the actual running requirements are performed.

An example simulational testing program, carried out to assess the actual force control behavior, has been widely done with employed industrial robots, (Fig. 7.34). The equipment was forced to follow different trajectories and its controlled behaviour did successfully perform the given tasks, always applying the prescribed normal pressures even when tracking very complex lines needing the simultaneous activation of the six axes. The results of (Fig. 7.35) are related to the tracking of a rectilinear path with time-varying reference force, exerted on a 100 kN/m stiffness environment. It is shown that the transmission of a sinusoidal forcer causes a noisy response in the position-commanded mobilities due to the engagement coupling, but the amount of the errors is quite small all along the duty range. (Besides that, after an initial transient, the force signal is tracked and preserved with nice approximation.)

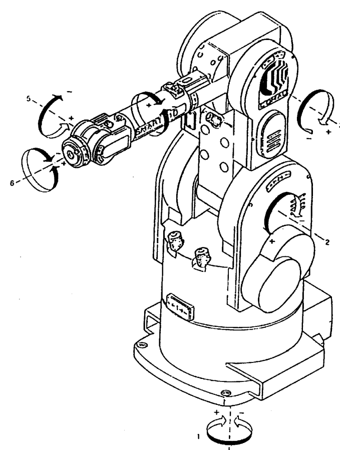

FIGURE 7.34 The Robot COMAU Smart 6.10R (courtesy COMAU).

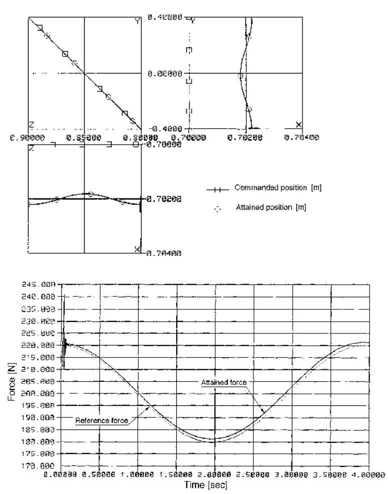

FIGURE 7.35 Reference and attained path for the simulation task (a) and for behavior of the manipulator (b).

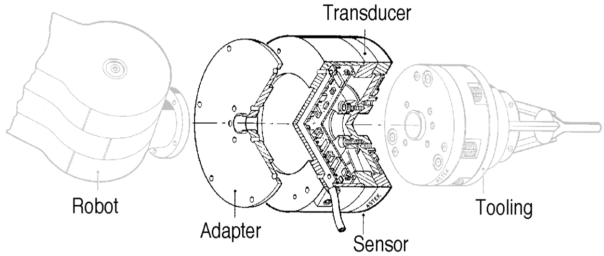

FIGURE 7.36 Schematic of a force/torque transducer.

The force feedback is, for the said reasons, employed for assembly and machining operations requiring comparative accurate skill. The simulated trials show that, for a given robot and equal applied forces, the performances slightly decrease as the stiffness function (13) of the robot-environment interaction increases. Force errors, however, stay within the range of the hundredths of the programmed set-points unless a rigid-wall engagement is approached. Beyond some given stiffness thresholds, in fact, the end-effector presents the wavering behavior with downgrading of tip attitude. As a general rule, for a stiffness ranging between 10 and 1000 kN/m and for the considered quite severe tasks, tests have confirmed the good performances that the existing robotic equipment could realize if provided with a control strategy that duly combines the position/force feedbacks during the work cycle with dynamic compensation along the navigation phase. Dynamics shaping assures high manipulation performance for very fast approaching paths. The force feedback grants adaptive end-effector operativity for a comparatively wide stiffness range. In fact, during constrained manueuvers, compliant arms operate on interfaced objects supported by compliant jigs, etc. The "computed" torque method deals with joint impedance effects requiring that the desired contact force is a function of the tip current position. When this function is poorly known, force and position are also, poorly assessed. The "measured" torque method by-passes such uncertainty, on condition, to put force sensors at the end-effectors or at the supporting jigs.

Expert Steering Commands: Compliant Assembly by Force Control

The introduction of a force/torque transducer at the connecting wrist, (Fig. 7.36), is still unusual for industrial applications due to extra costs of the setup and also in terms of the current programming software. However, the independent measurement of the force/torque components exerted by the robot tip is being viewed with increasing interest since efficient and low cost instrumented wrists started to become available. Haptic manipulating feel, indeed, is being considered for instrumental robotics as an additional opportunity to expand versatility and dexterity up to (and above) the range of human potentialities. This is a critical requirement; for instance, to technically and commercially assess the appropriateness of the devices of the emerging fields of micro-machines and of micro-dynamics. Touch information is, in fact, useful for modulating the feedback in order to keep "sufficient" stability margins to the robot motion, while the task progresses.

It has been demonstrated, [AnH89], that independent position-and-force controls may lead to instability. Unless the overall dynamics is taken into consideration, to reset the feedback gains by writing the manipulation laws directly in terms of the effector frame (which does not correspond with the work frame anymore) with joint weighing the 'robot-arm and coupled-environment' process. Due to the variety of real occurrences, however, the models for combining position and force controls should be assessed only about actual task situations. These models usually consider a global work-space frame $G\{y\}$ separate from the tip frame $P\{x\}$, which follows the strain of the interfacing medium. Unless for very high stiffness, the relations (7.7) and (7.12) have to be modified to include the transforms between these two frames:

$$y = Tx \quad F = G(s)x \quad \text{with: } G(s) = Ms^2 + Hs + k \tag{7.15}$$

$$F^* = T^{-1}F \quad F^* = G^*(s)y \quad \text{with: } G^*(s) = M^*s^2 + H^*s + K^* \tag{7.16}$$

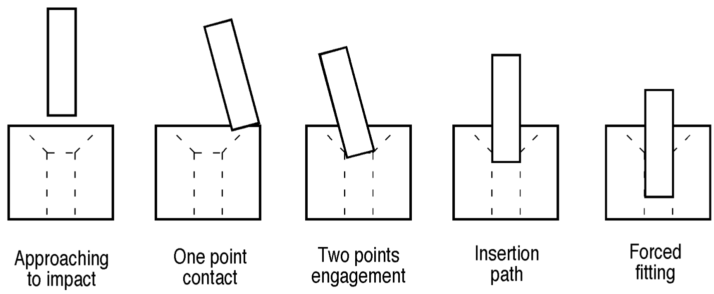

FIGURE 7.37 Assembly with reactive steering.

The CAD facilities are useful to specialize the knowledge setup required in order to establish the programs for tasks scheduling; to fix the agendas for job planning; and to design the decisional schemes for operation testing. Expert supervisors follow joining continuous controllers for the work phases with the logic steering of the task depending on the acknowledgement of given thresholds. A typical study deals with plugging a part in a (prepared in advance) seat (slot, hole, etc.). The reference phases would cover: part picking up; approaching motion; and insertion with check of operation soundness. This last conveniently splits into sub-phases aimed at the simple "peg-in-hole" forced fitting, (Fig. 7.37). Several situations may arise and condition monitoring by the wrist transducer provides the visibility on the process, to grant the result.

The situational analysis is performed by the '*expert*' supervisor, recognizing:

- The peg collision feature at the end of the navigation path, with a preliminary guess about the engagement line slant;
- The peg tilting feature at single point bump, with identification of topology constraints due to the front seat shape;
- The peg engagement feature at two zones contact, with assessment of tip maneuvers to recover the proper attitude;
- The peg insertion feature at the forced operation, with path control to keep zero offset for the wrist torque;
- The peg fitting feature, at the plugging end, with stroke settling as for specifications and actual part mating tolerances.

Monitoring provides information about incorrect settings, such as jammed or loose fit; the force-torque sensor, (in addition to the steering commands), makes it possible to acquire the data for on-process quality checks.

The assembly task, according to the said description, is an occurrence-driven process with relevant advantages supplied by an "expert" supervisor typically incorporating a heuristic decision logic process. Instrumental robotics will possibly consider special applications such as those of the micro-dynamical systems where the option would bring noteworthy advantages, thus, leading to fixtures with return-on-investment. The domain of sophisticated fixturing is further discussed in the next section with focus on the possibility of functional redundancy in addition to the command redundancy.

7.5 Redundant Mobility Robots with Cooperation

Operation-driven design is powerful help for setting robot's effectiveness, provided that functional models are stated detailing manipulation dynamics up to the certainty ranges of the needed performance figures. The field of instrumental robotics is fitted up by talented solutions for factory automation. Industrial manipulators support most of the work cycles and only loosely assessed manufacturing processes meet drawbacks, such as surface deburr. Most of the time, the enterprises in these cases have resorted to hand interventions when geometric constraints, edging compliance, shape variability, and tolerated span represent a highly demanding mix of requirements despite unsteady machining patterns. Automated deburring, in fact, now runs into deficiencies when modeling the process and this prevents accurate and efficient issues. The fixtures have perhaps been developed by miming too much manual habits, even if no reason at all exists that task-oriented solutions should profit by anthropocentric rules. By this conventional approach, a deburring robot presents a performant manipulating arm, with the finishing tool at the tip, conveniently actuated and extensively sensorized. It's functionality shows limitations, that actually, a skillful and trained operator overcomes with craft and ingenuity, adapting the operation modes to the task progression.

The switching to robotic equipment for precision deburr has to be reached by looking over the process again, to establish a setup aiming at smooth engagement; position-and-force control; steady repetitiveness; and, in general, highly adaptive fit-outs based on skillful survey of the work progress to restore correctness. By robotizing, once accuracy figures are achieved, productivity and tolerances are preserved according to total quality conditions, therefore, assuring improved product finishing as compared to manual operation. Robotic equipment, with cooperation, is an important alternative to be considered. The example case addresses this target. The deburring tool is operated by a six degrees-of-freedom arm. The work-piece is borne by a similar six degrees-of-freedom rig whose mobilities are controlled to interact with the machining end-effector. The rig, in this context, reduces to a platform whose position and attitude are driven by task-oriented requests. Functional innovation, "cooperation" task setting, is related to the ability of establishing work sequences that depend on the deburr cycles to be executed. The dynamics of the bearing rig and of the operating arm need to be programmed concurrently.

To that purpose, the analysis of the cooperation opportunities is the preliminary step to correctly and efficiently integrating work and handling facilities. This can be done with the already mentioned package SIRI-MR which combines a series of blocks; that is, (SIRI-CA) for configuration analyses; SIRI-AD for dynamics generation; and SIRI-SC for control strategy choice. With the SIRI-MR package, a virtual reality duplication of the multi-agent 'environment' is provided to characterize robots cooperation. A design sequence with SIRI-MR presents as follows:

1. *Specification of functional cooperation figures*: primary goal is paths selection and tasks timing. The SIRI-MR package is employed as "planner-frame" (essentially based on the SIRI-CA block) and between "feasible" paths of the individual arms, the 'job-consistent' trajectories for the multirobot system are singled out.
2. *Specification of operational coordination figures*: this second design step is aimed at trajectories setting and control trimming; to change "feasible" dynamics into "tasks-consistent" dynamics; and the SIRI-MR package is employed as 'controller-frame' based on the SIRI-SC block with the included SIRI-AD block options.
3. *Specification of multirobot performances*: efficiency testing and accuracy check are performed on job-consistent (according to given functional cooperation figures) paths and with tasks-consistent (according to the chosen duty coordination figures) dynamics. The SIRI-MR package is fully enabled as "cooperation-frame" according to the selected duty (Fig. 7.21), task (Fig. 22), and govern (Fig. 7.23) modes.

The following presentation refers to the above ideas to exemplify how cooperating fixtures are selected to supply process attuned solutions. The deburr process is reviewed first; then discussion is turned to a powered platform purposely built as a cooperating rig when provided by position/attitude commands with control of the interfacing force components.

Process Conditioning Environments: Deburr Operations

Machining of work-pieces commonly results in burrs left on material bodies. These burrs have to be removed, due to piece safe handling, fitting, or assembling, because of functional requests on the surface shape (e.g., for fluid flows mating) on the body properties (e.g., stress intensity concentrators relief).

Today, burr removal is still mostly carried out by hand, which means a time-consuming and boring job. Finishing moreover, highly depends on skill and mastery of trained workers. Since labor becomes more and more expensive, artifact's cost is influenced considerably by this process. In some cases, the deburr process causes 35% of the final price [KBK86]. In addition, manual burr removal does not allow persistency of tolerated figures and replication of exactly defined chamfer profiles which is critical for a variety of artefacts. This so-called precision deburring is, however, requested to reach total quality, particularly in the production of diversified turbomachinery blades and nozzles (to reduce turbulent flows); the manufacturing of gear, shaft, or cranks (to relieve local stress); the assembly of high speed rotors (to keep dynamic balance); or etc. By robotic deburring, moreover, the reject rate of products would be far lower. In the near future, automatic burr removal processes could aim at zero-defects production and wider exploitation of the equipment, today developed as technology driven contrivance might become a market driven option for factory automation.

For robot execution, the process shall first be quantitatively modeled; starting with a proper estimation of burr size and shape [HoG87] , [KWB88], [AsT96]. To satisfy finishing results, the fixtured unit should be able to avoid the so-called "worst case burr"; namely, a maximum size burr occasionally occurring when the machining forces do not concentrate according to given geometries. The amount of material to be removed per unit time, Fig. 7.38, the so-called "material removal rate" (MRR), can be expressed by a simple balance:

$$MRR = (A_B + A_C)v_T = A_C(R_M + 1)v_T \quad R_M = A_B/A_C \tag{7.17}$$

where A_B is the burr's cross sectional area, A_C is the chamfer's cross sectional area, and v_T is the tool speed along the edge to be deburred, (Fig. 7.38). Of course, the mentioned areas can be expressed in function of other parameters such as contact forces, strength of the material, etc., to connect geometries, strains, stresses, and machining operations.

The tangential area ratio: $R_M = A_B/A_C$, typically varies between 0 and 2 depending on burr size, where the value 2 refers to "worst case burr." In practice, large variations causing diversified situations need to be faced. Process variability ranges need to be further analyzed to fix standard reference figures. During deburring, the normal F_n and the tangential F_t components stress, (both robot and piece). The current cross sectional area of burr and chamfer, therefore, depend on both the normal and tangential projections. Then, the variation of normal and tangential components (ΔF_n and ΔF_t) is related to the respective projections of the cross sectional areas of burr and chamfer, that is:

$$\Delta F_n = f_n(\Delta A_B/\Delta A_c)_n \quad \Delta F_t = f_t(\Delta A_B/\Delta A_C)_t \tag{7.18}$$

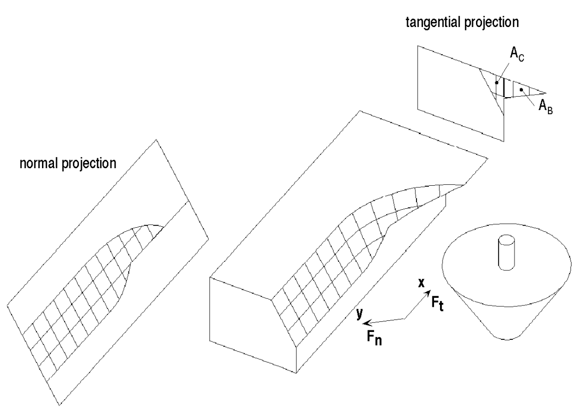

FIGURE 7. 38 Details of the burrs removal process.

Of course, the chamfer normal and tangential projections do not depend on the burr size. On the contrary, the burr size modifies its cross sectional area projections. Burr size, more precisely, greatly affects the tangential force F_t, whereas it has considerably smaller affect on the normal force F_n. Moreover, a constant chamfer surface quality is required regardless of burr size. This means that the material removal rate (MRR) shall remain steady; otherwise, the dressing process with small burrs suddenly changes to rough-machining process, yielding the "worst case burr" occurrence with bad surface finishing. Since R_M varies between 0 and 2, the control system must monitor the variations of F_t, and F_n and modify the tool speed to keep MRR constant. The option requires control of the mutual positions of the tool cutter and the piece surface attitude with closure of independent force/torque feedbacks. The analysis of the deburr process [PeV96], [RLC97], [KBK86] shows that the proper robotic solution should carry on, in parallel, the position/attitude command and the force/torque modulation at the engagement boundary between cutting tool and compliant surface.

A six mobilities arm, without force feedback, suffers from considerable drawbacks, represented by three-dimensional vibrations that upset the chamfer path. This results in unsatisfactory surface edge quality which is important in precision deburring. The wavering behavior depends on the discontinuities of the exchanged machining forces and on the compliance of piece supports and tool drivers. An attempt at preserving the finished surface quality has been sought through stochastic control [Pek64] or by means of adaptive end-effectors. Redundant mobilities can be added at the deburring front-end, in the way that the conventional 6 d.o.f. serial arm makes the main engagement (e.g., force control setting) and the extra mobilities carry out secondary compensation (e.g., position trimming). The set-up could be explored through passive adaptation. As usual, the behavior of the fixture is described by a mass-spring-damper model with normal direction mechanical impedance (ratio of contact force to end-effector deflection, as a frequency function) given by:

$$F_n(j\omega) = G_n(j\omega)x_n(j\omega) \quad \text{with: } G_n(j\omega) = (K_n - \omega^2 M) + j\omega H_n \tag{7.19}$$

A large normal impedance causes the end-point to balance grinder forces remaining close to the pre-set trajectory. Given the volume of metal to be removed, the desired tolerance in the normal direction prescribes that the value of this impedance shall not exceed conditions yielding burr excitation resonance. At the same time, it is necessary not to produce high tangential contact forces since tool stall (or even breakage) may occur with dangerous normal skips. It follows, Eqs. (7.18) and (7.19), that the end-effector needs to operate all along with bounded interaction forces which implies small tangential impedance. On the other hand, uncertainties in the end-effector position are smoothed by a large compliance in the normal direction, at least up to the robot resonance range. All in all, the end-effector shall show the following behavior in the normal direction:

$=> |G_n(j\omega)|$, large for all ω in the ω_R band; $|G_n(j\omega)|$, small for all ω in the ω_B band;

$=> \omega_R < \sqrt{K_n / M} < \omega_B$ where: ω_B, burr resonance range; ω_R, robot resonance range.

The Automation of Precision Deburr Operations

It is possible to design a passive end-effector with such dynamic characteristics but it would be impossible to let it also meet the condition on the tangential direction (large compliance). Because of the role played by the constant mass of the grinder, making equal the dynamic behavior of the end-effector in both directions at high frequencies, when a large normal stiffness is chosen to improve the quality of the surface finish, and then the end-effector will not be compliant enough to compensate for robot oscillations. This is why an active system is required to optimize the process parameters and to compensate for robot oscillations while showing large stiffness in the normal direction [BEL91], [HeK91], [YOY94], [KIK90], [KuW92], [StS90], [VaP96], [WET90], [WhT92], [WKT90]. Active dynamical systems can either operate by control redundancy or by functional cooperation. In the first case, distinct position/attitude and force/torque sensors are used to accomplish redundant tool-tip control. The setup still suffers deficiencies as the uncoupling of normal and tangential behavior is hindered by inertial effects of the equal massic terms. As for functional cooperation, redundant mobilities are required, namely:

- Addition of independently actuated members to the arm (serial d.o.f.) [YHM94];
- Inclusion of an actuated rig for holding the piece to be deburred (parallel d.o.f.).

The first solution suffers from given snags: low stiffness of the open chain with critical control setups constraints requiring nasty trimming and arduous presetting operations; and band limitation in particular with variable operation ranges depending on extended mixes of pieces to be deburred.

The second solution offers several advantages:

- The redundant mobilities extend versatility and dexterity enhancing the robot accessibility along the surface edge to be deburred. The rig d.o.f. can be used to hold the piece in a pose that favors the robot end-effectors work-trajectories;
- The adaptivity can be upgraded by intersecting paths operation modes with efficient sweep of the workspace and exploration of task planning which avoids collisions at engagements or undue penetration during deburr;
- The efficiency can be improved: the execution times can be reduced with low absolute speeds of each cooperating robots, but high relative speeds of the work-tip;
- The same accuracy can cover the full workspace; robot position/attitude along the main movements may be compensated by the position/attitude tracking of the cooperative rig, which is responsible for the servoed movements;
- Critical tasks can be faced with repetitiveness: sharp corners, for instance, are tracked without considerable speed reduction by obtaining smooth paths by split tracks (this is important for precision deburr, when corner-rounding is not admissible);
- Closed kinematic chain allows a lighter rig design which results in lower mass inertia and better dynamic behavior of the cooperating equipment used to get rid of the partner robot oscillations, as is the case with precision deburr;
- Further quality and efficiency betterments are obtained by adaptive job planning aiming at preventing worst case burr or, at least, avoiding uttermost courses within the variability range of the removed burrs.

Obviously, there are certain drawbacks, too. Two robots, instead of one, result in higher costs. Coupled motion requires more sophisticated control which further increases costs. Programming is more time-consuming compared to a single robot, particularly in case of adaptive path planning and tightly bound dynamics. These handicaps are reduced when proper standardization is reached by the cooperating rig, the control architecture, and the programming aid. In the first instance, the in-parallel actuated platform offers quite an effective option. It is close-packed, easily powered, and suited for position/attitude tracking. Control and programming burdens are drastically reduced by referring to CAD packages, such as the SIRI families of codes, and using them for the design, development, setting, and fitting operations in virtual reality surroundings, all along the robots life-cycle.

A Cooperative Fixture for Work-Parameters Adaptation

The cooperating engagement of the piece-supporting rig needs proper performance in terms of position tracking ability, reactive stiffness, attitude controllability, etc., in a way to upgrade arm's accuracy, dexterity, efficiency, and versatility according to requests. The mechanical architecture of this rig is based on an in-parallel actuated platform (originally designed at the Polytechnic of Turin [RoS92], to support assembly operations). The development has also been studied [ACC94c], in view of micro-robotics applications [ACM95]. A solid model of the fixture provided the principal features of the rig. It consists of a platform, actuated, in parallel, by three driving blocks, each one displacing a vertex of an equilateral triangle which specifies attitude and position of the reference plane. Each driving block is obtained by

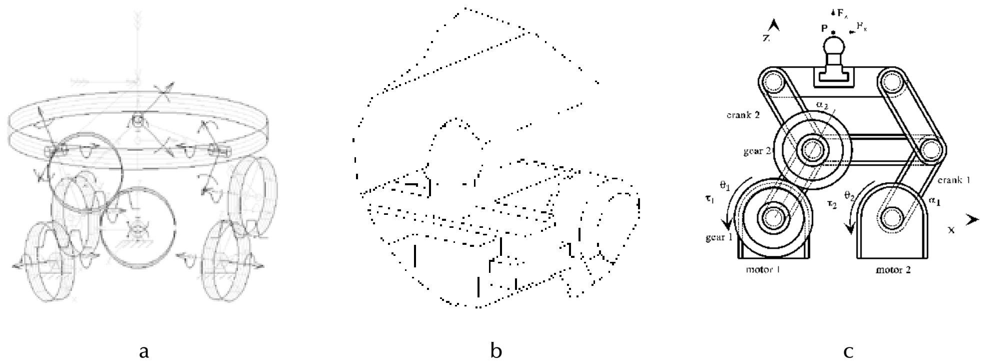

FIGURE 7.39 The powered co-operating rig example: (a) multibody model; (b) linking of table and upper parallelogram (particular); and (c) side view of one platform's driver.

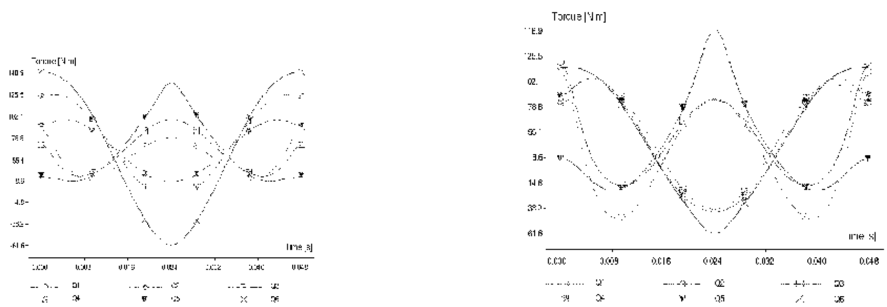

FIGURE 7.40 Inverse dynamics: plot of required torques [N m] (a): full payload (5 kg) – (b): no payload.

two superposed planar parallelograms moving vertically. The platform is fixed to the upper parallelograms. The linking is assured by spherical bolts that are impinged at its lower side and can also slide along guideways, fixed to the top beam of the upper parallelogram. The guiding slots, placed orthogonally to their carrying beams, form an angle of 120° between each other; the coupled parallelograms have beams linked by ball bearings to reduce friction. They are driven by a pair of DC motors, solid with the rig base to reduce the inertial effects. For position accuracy, the upper four bars, Fig. 7.39, are moved by a backlash-free gear train, not linked to the bottom cranks; the lower four bars are directly driven by the twin motor.

The setup repeats three times and the final the assembly with the plate results in a system with six degrees of freedom; thus, the rig has six servo-motors to be controlled. The rig dynamics has been analyzed [MAC97], by assessing

- The actuation kinematics using the geometrical constraints to model the forward and backward mappings, which link workspace and platform control coordinates; and
- The open-loop dynamics combining inertial terms and constrained motion to generate the reflected loads on the driving commands.

The modeled platform was used for the functional validation of the cooperating rig. The prototype weighs about 5 kg and is supposed to be able to carry a same amount as pay-load. The working space is small with path continuity hindrances at the out-boards but the platform is requested to accomplish only small oscillations around its "central" positions. Both direct and inverse dynamics simulations have been performed: the imposed trajectories of inverse simulations have been chosen to be straight lines (in the working space) tracked with sinusoidal time laws. The period of the sinusoids has been chosen so that maximum accelerations around 1 g are obtained, except the few cases in which high acceleration motions (10 g) have been considered. Fig. 7.40, for instance, shows the torques needed to track an oblique

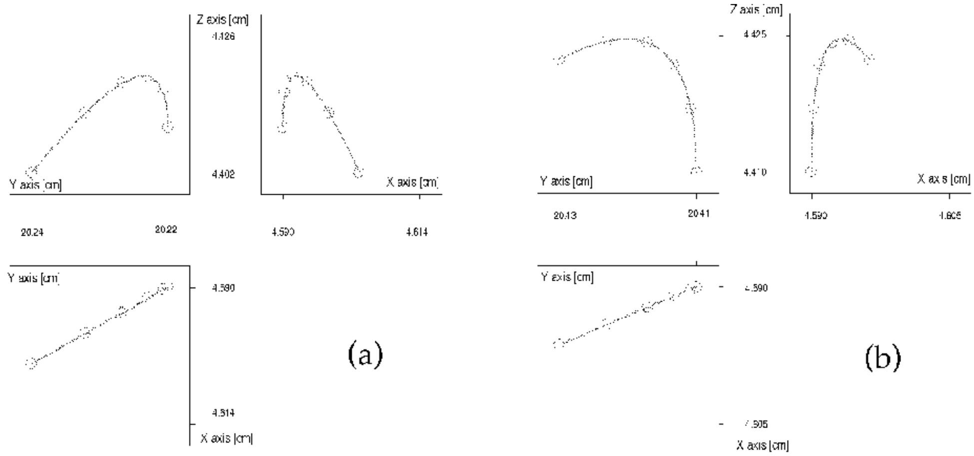

FIGURE 7.41 Direct dynamics: orthographic projection of platform's free motion (initial vertical velocity of 0.1 m/s): (a): full payload (5 kg) (b): no payload.

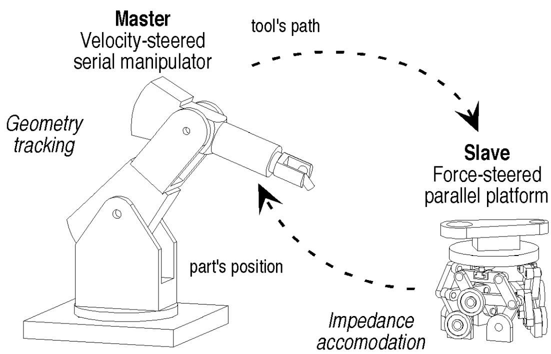

FIGURE 7.42 Block-schema of a deburr stand with cooperating robots.

straight line of 3 mm stroke with change of attitude about a "horizontal" configuration, with and without the maximum allowed payload. Figure 7. 41, instead, shows the three orthographic projections of platform's free motion paths, when an initial vertical velocity of 0.1 m/s is assigned.

Comparison of results obtained by several test cases provides the main characteristics of the equipment.

- The global dynamical behavior of the system is mainly affected by the dynamics of the actuation system, as the contribution of the payload/table group is quite negligible.
- The motion is more easily obtained when it is parallel to one actuation side rather than normal to it.
- As already pointed out by other researchers [SoC93], the working space is considerably restricted.
- Compared to the small-scale realizations [ACM95], the equipment is moderately sensitive to the influence of the gravitational field.

This kind of fixture deserves particular interest for its ability of accurate tracking, in position and attitude, any three dimensional surface. The rig, Fig. 42, simultaneously controlled with the arm equipped by deburr chamfer gives rise to a redundant mobilities setup. Joint force-and-displacement governing strategies can be enabled to reach the very high versatility and dexterity figures of human operators while improving the efficiency achievements with operation continuity and the steady accuracy of the surface finishing by an impedance control, with the displacement term represented by the relative motion between the deburring robot and the supporting platform.

The Impedance Control of the Cooperating Fixture

As noted on pages 7–31 through 7–33, the starting point of impedance control design is the choice of two stiffness K_P and damping H_P matrices to obtain desired coupling effects at the tip or, which is the same, to have interaction forces at the interface given by

$$F_E = K_P(x - x_d) + H_P(\dot{x} - \dot{x}_d) \tag{7.20}$$

Such external forces are, of course, independent variables and the motor torques can be computed so that the actual tip displacements are related to the developed forces (7.20), for instance (for gravity compensation) by applying

$$Q_P = B(q_p) - J^T(q_p)[K_p(x - x_d) + H_p(\dot{x} - \dot{x}_d)] \tag{7.21}$$

This approach, thus, consists of monitoring the dynamic relationship between force and position, rather than separately measuring the two quantities. It must be noted that, by varying the K_P and H_P matrices, either a force control or a trajectory control is obtained. In fact, by increasing the values of the stiffness elements in the K_P matrix, the control system tends to keep the end-effector closer to the assigned path; while a decrease of such values ends up with a more compliant end-effector. Commonly the H_P matrix is chosen to reach critical damping along the trajectory controlled directions.

Stiffness and damping matrices are usually expressed in a local work-frame $\{L\}$, attached at the piece in the contact point with the tool and with x and y axes parallel to the tangential and normal directions. Therefore, calling K'_P and H'_P these local matrices, a time-varying mapping with the global frame $\{G\}$ is needed. That is why, also in case of constant process requirements, (i.e., fixed stiffness and damping values for the various directions) actual K_P and H_P matrices change during normal contouring operations.

$$K_P(q_P) = {}^L_G[R(q_P)]^T K'_P \, {}^L_G[R(q_P)] \quad H_P(q_P) = {}^L_G[R(q_P)]^T H'_P \, {}^L_G[R(q_P)] \tag{7.22}$$

where ${}^L_G[R(q_P)]$ is the rotation matrix between global and local frames.

The stiffness matrix K'_P can be selected diagonal with principal elements chosen to grant the desired compliant task; namely, the terms related to tangential translations have low values (i.e., the interaction is characterized by low stiffness) for the direction along which force must be limited; the terms for the directions along which trajectory has to be controlled, i.e., and the other two directions have large values (only limited by the available control bandwidth). The matrix H'_P is, moreover, chosen to be diagonal and composed of the desired damping coefficients in each direction with critical damping selected along trajectory controlled directions. As for rotations, the requirement is to follow the assigned attitude as close as possible. The related (high) stiffness, accordingly, will be isotropic in the working space. In this case, best choice seems to be the use of the equivalent angle-axis representation that expresses the rotation between reference and actual tool frames giving the axis r along which rotation occurred and the related angle ϑ . Thereafter, the relation (7.20) is preserved for the impedance control of the linear motions, while for the rotational ones, the following equivalent formula is used:

$$M_E = k_P \vartheta r + h_p \omega \tag{7.23}$$

The setup is completed by the compensation of gravity terms via feed-forward cancellation of the related contributions. Exact compensation can be computationally heavy as the full forward kinematics, which are rather complex [ACC94c], shall be evaluated on-line. A good compromise is the off-line evaluation of the gravity terms corresponding to the assigned path, with their on-line updating, Fig. 7.43, at lower rates with respect to the inner control loop. Computation of the trimming terms and reflection to the motors are easily performed once the dynamics is known [ACM95], [MAC97].

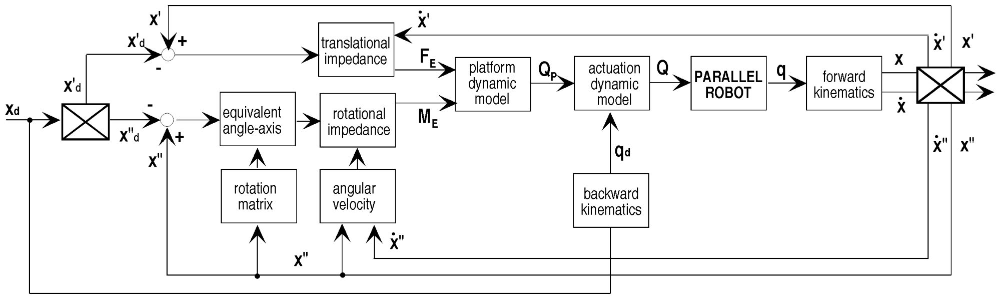

FIGURE 7.43 Scheme of the impedance control system (prime symbols are related to translations and double prime to rotations).

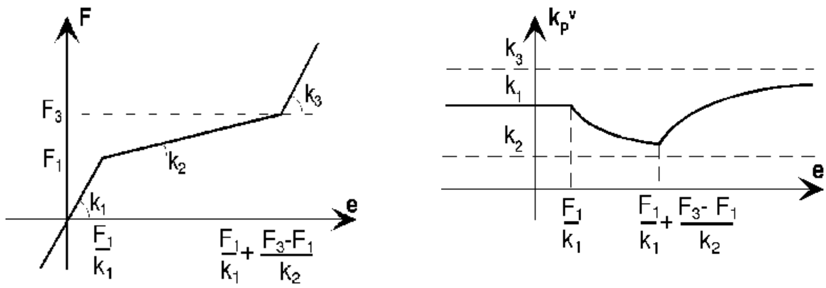

FIGURE 7.44 Variable structure stiffness (a) and virtual equivalent stiffness (b).

A further improvement can be obtained, for the present application, by adopting a non-linear law for the stiffness along the tangentia direction, Fig. 7.44. The "optimal" value (k_2) can be used for working conditions near the reference state while the compliance is stiffened if the tool is working outside the standard range. By this way, even for difficult tasks, the need of resetting the cooperative fixtures (serial robot and platform) is almost avoided. In fact, if the platform is going out of the working space, an increased stiffness brings the reset to standard working conditions. To be able to keep the usual matrix forms, a virtual stiffness k_s^v is introduced with the behavior shown in the Fig. 7.44, plotted against the position error e in the tangential direction. The related damping factor k_s^v must be accommodated accordingly, within the same working range.

The whole system has been studied by computer simulation with Pro/MECHANICA (by Parametric Co.). It is a complex multibody package that has been used to solve the complex DAE model of platform dynamics and to test the proposed control system. Several tricks have been used to simplify the model while preserving the correctness of the dynamical behaviour and finally, Fig. 7.39, a fixture with 10 parts and 9 kinematic pairs has been worked out.

To perform a few simulation trials, the deburring process model was also needed. With reference to the above considerations, this has been particularized for the case of deburring of aluminium aeronautical components, for which many experimental data were available [Hic85], [KiH86]. Therefore, the tangential and normal forces between tool and component are synthetically expressed [JKL97], [Jok97] by experimental relations:

$$F_t = F_t(V_{\text{tool}}, \omega_{\text{burr}}, \dot{x}, x, t); \quad F_n = F_n(V_{\text{tool}}, \omega_{\text{burr}}, \dot{x}, xt) \tag{7.24}$$

with t, time, x, $\dot{x}$ displacement and velocity of platform in tangentialdirection, V_{tool} velocity of the tool, and ω_{burr}, frequency of the surface grooves.

The presence of the motors modifies the system's response and the described model needs to be augmented with the addition of a (first order) dynamic block for each torque motor. As expected, the overall response is affected by higher damping. Then, to finish a surface with a steady undulation (left by previous

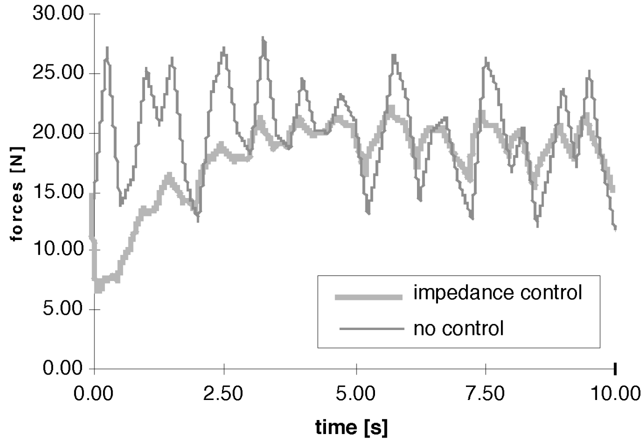

FIGURE 7.45 Simulation output: deburr forces with and without compliant fixture.

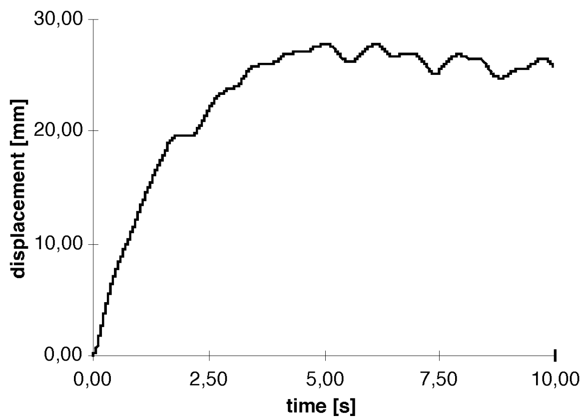

FIGURE 7.46 Typical results: platform tangential displacements.

machining), the transient trend, Fig. 7.45, shows the slight accomodation of the sinusoidal interaction force and features the relevant path stability, Fig. 7.46. Once the system that is charged by the sudden force and torque step comes back home, the surface finishing, it shall be pointed out, does not depend on global displacements (rather only on the relative displacements).

This control, as expected, characterizes, by simplicity and robustness, parametric uncertainty even if with limited dynamic performance. Indeed, it is not required to explicitly solve the manipulator inverse kinematics, since the actuation law is given in terms of work-space errors; moreover, it does not require measurement the interaction forces or to explicitly assess the environment stiffness.

The Multi-Robot Assembly of Compliant Components

The domain of robots with cooperation opens several other possibilities as in the case, for instance, aiming at improving assembly effectiveness. During the joining tasks, some components may characterize by large compliance and settling cannot neglect the mutual deflections during processing. An automotive body, for instance, is composed of different bent sheet metal pieces; these are positioned by clamping rigs to be spot welded into parts, further handled to be joined together to form structural bodies (passenger compartment, engine box, rear trunk, wheel shields, etc.). To achieve proper dimension tolerances, the shaping accuracy around some 0.5 mm is needed, regardless of sheet warping, by quick and reliable part positioning. Valuable aid is supplied by multi-robot assembly, based, e.g., on a position-controlled master with a force-controlled slave.

In front of large compliances, a better set-up would address a coordinated control, with a supervisor steering two robots, Fig. 7.47, each holding a deformable payload, (Fig. 7.15), to be positioned and joined together, within tolerated figures. The analysis develops by modeling the components of known compliance, so that the navigation paths bring the pieces with due assessment of their perturbed geometry, Fig. 7.48. For assembly, (e.g., the (outer) forged sheet-steel and the (inner) pressed trimming face) to obtain a car door, some simplifying assumptions are, generally, say,

- The manipulator links and transmission compliances are neglected;
- The effects of the gravitational potential energy are omitted;
- The grip zones hold both pieces without local energy storage build-up;
- The back-coupling of the pieces strain conditions on the arm is ignored;
- The contact mechanics assumes the central impact between matching shapes;
- The pieces joining is fulfilled by a single stroke with damping out of the efforts;

and other similar hypotheses, to bound the overall degrees-of-freedom in handling and assembly.

The dynamics of the cooperating robots will, finally, be described by using the model (7.5) for the free motion phase, followed by the linearized approximation (7.8) as soon as the joining operation starts. The interfacing force δF_E is given by assessing the contact model between the cooperating robots grip points with interposed compliant payload. The description consists of separate coordinate frames for each tip and

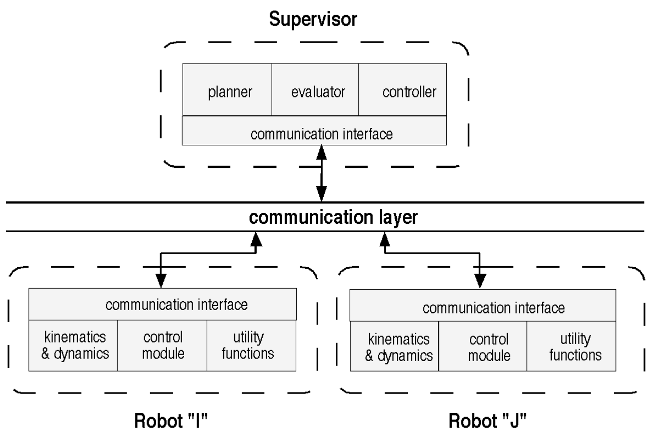

FIGURE 7.47 The coordinated control architecture of multi-robot fixtures.

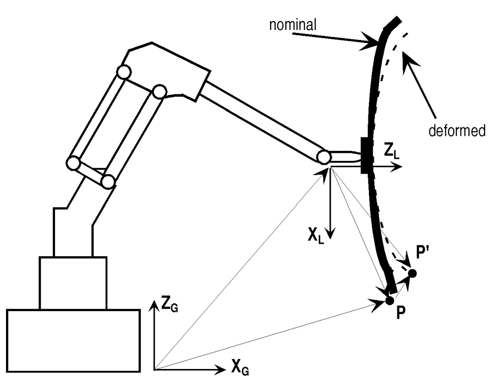

FIGURE 7.48 Handling model for the carried compliant shells.

for the workspace using the transforms (7.15) and (7.16). The last could possibly be omitted, by enabling a steering logic for bringing the joining movement to follow a normal direction with respect to the clinching surface. Thereafter the contact model is simply expressed by the reaction force at any of the grip points:

$$F^* = G^*(s)y \tag{7.20}$$

where y-relative displacement vector between tips.

The identification of the generalized mass, damping, and stiffness can be obtained by means of a finite-elements code, directly used to study the strain behaviour of the pieces once the contact is established. A detailed investigation is given in [MiI96], with rather extended simulation results. All things considered, an effective assembly stand can use standard cylindrical arms to accomplish the picking and approaching maneuvers; the wrists shall properly allow small accomodations, say:

- Angular shifts:—pan, around a vertical axis;—tilt, around a transverse horizontal axis;—yaw, around a normal horizontal axis; and
- Linear shifts: vertical and lateral moves aside;

while the linear move for clinch fastening is, as said, impressed through the arms by an impedance control.

The set-up leads to effective solutions on condition of slightly modifying the pieces (for safe feeding and handling). The transposition of similar arrangements to micro-manipulation tasks deserves special attention especially in front of duty sequences in the microscopic range out of many possibilities.

7.6 Conclusions

The development of instrumental robots has been addressed in this chapter, mainly as a "technical" problem looking for "highly effective" rigs according to function-oriented requirements. The goal is basically related to the capability of modeling the devices' behaviour. Several texts, [Ard87], [AsS86], [Cra89], [Koi89], [Pau81], [Riv88], [VuK89], [FGL87], [McK91], show how to obtain the manipulators dynamics, based on the Lagrange's approach or on the Newton-Euler equations. Suitable computer codes are, as well, already available to provide solutions at different levels of accuracy. The issues, however, could suffer 'economical' drawbacks when the robot abilities happen to be overemphasised as compared to the duty actually required to achieve the instrumental scopes. Therefore, "leanness" is not stressed enough to address artifact-and-process re-design and all business re-engineering, so that the finally chosen instrumental robot will perform the assigned tasks with no function, duty, or resource redundancy.

On such a preamble, the design activity will outgrow the possibilities of most teams and only iterative attempts might try to approach "balanced" solutions, on condition of being able to assess the fixtures actual behavior, within real operation conditions. The "obvious" idea of experimenting on prototypes is not considered while rising costs and the interacting surroundings will sometimes supply incomplete, incorrect or improbable settings. This is the main reason for developing the CAD series of packages, such as the SIRIxx environment, Fig. 7.49, to have an integrated reference for assessing the controlled dynamics of task-oriented high-performances manipulators by virtual reality testing.

The virtual reality simulation is used as CAD support in the ideation and technical specification phases of the equipment and helps, as off-process reference, for tasks programming and control tuning, each time the actual use of the equipment needs to be modified. The main feature of simulation is that it allows different types of analyses (so that it covers most advanced performance robotics requirements) by integrated knowledge frames (in order not to lose the specialization effectiveness, aiming at each sectorial field application). An illustration of the capabilities has been given, emphasizing the ability of shaping the dynamics and of managing the redundancy.

The design of an instrumental robot starts by acknowledging sets of competing task-driven solutions, supporting the setup of highly effective operation modes. Structured functional models must be established,

SIRI-AD [AMM84b]	The nonlinear manipulation dynamics is generated, for open-chain arms with any number of mobilities and joint connections; the interfacing with 32 modelers helps the computation of mass quadratic moments and the location of mass centers.
SIRI-CA [ACM86]	The trajectory planning is provided for 32 families of open chain manipulation set-ups, by means of algorithmic models describing both forward and backward kinematical transforms; parametrized standardizations are available
SIRI-CL [ACM96c]	The kinematics and the dynamics of 2 families of closed chain manipulation set ups are established with parametrical models; topologic analysis criteria are given for the closed chain set-ups commercially available
SIRI-SC [AMM87]	The control planning is established for open-chain arms with any number of mobilities and joint connections, referring to an expandable library of strategies; the dynamics shaping with nonlinearities compensation is considered
SIRI-AT [CMP94]	The manipulators postures/shapes are given with virtual reality restitution, to investigate the work-space singularities (collision avoidance, etc.); *by-default* blocks automatically generate solid members, once lengths are available
SIRI-MR [AMM91b]	The robotic systems with cooperation are provided, for performing trajectory and control planning for master/slave setups, for supervised coordinated robots, for parallely operated fixtures, etc. when operation redundancy is used
SIRI-HD [AMM91a]	The command redundancy with force and/or position feedback is provided, for adaptive task planning (and dynamics shaping), with and without state expansion by modeling robot-surroundings interactions
SIRI-UM [ACC94b]	The *engagement* phase (between the *navigation* and the *work* phases) is given with different collision and bouncing conditions; the description is parametrized for including the results from experimental investigations

FIGURE 7.49 Synoptic presentation of the main SIRIxx packages.

so that the dynamics of each robotic equipment can be generated throughout assessment of the accuracy, dexterity, efficiency, and versatility figures achieved by each particular solution.

Once the functional models are available, the design procedure extensively exploits CAD-based tests for virtual reality experimentation before actually building prototypal devices that might fail to reach the requested technical and economical effectiveness. The approach success, however, depends on the appropriateness of the model. In fact, whether reductive equivalencies (to lower the degrees of freedom), approximations (to suppress nonlinearities), motion constraints (to simplify cross-coupling effects), etc. are not properly stated, the generated dynamics does not provide correct reference to assess the robot performance, in terms of accuracy, dexterity efficiency, and versatility.

The engineering practice suggests different ways for "proper" modeling and we have already pointed out how developments in instrumental robotics will share the methods of the integrated design activities. As a general rule, it is worth distinguishing

- The manipulation dynamics: the forced motion of hinged solid bodies in the joint-space is the basic model with the unavoidable transport effects of inertial terms and Coriolis acceleration. The refining might cover: joints and links compliance; transmission and actuation effects; etc.
- The interfaced surroundings coupling: the constrained motion of the robot tip, active in an independently defined workspace, is the basic model with (possibly) reduction to joint-space driven-commands through "impedance" control state extension with account of the measured variables.
- The logic steering govern: the programming abilities are the basic means to deal with task variability and with occurrence uncertainty. Shallow knowledge models are used to expand the relational frames with "expert" modules, having overseeing and decision support functions.
- The monitoring of actual returns: value cycle models are defined to assess the real cost of the innovation in terms of beneficial fallout on the products once potentialities are fully explored (including on-process exploitation of quality data), so that checks are run on the economical side.

The chapter concern is, mainly, to design instrumental robots whose performance is driven by the capability of accomplishing a given set of tasks. Then attention is focused on the deep knowledge needed to describe their dynamics. The addition of nonexploited abilities results in unacceptable costs; thus, the reasonable connection between tasks domain and functions assignments has to be done from the ideation steps to understand the technical appropriateness of each prospected solution in terms of actual returns. To that purpose, the SIRIxx environment provides the conditioning references, in terms of structured (deep knowledge) constraints. Technically "advanced" options have, in particular, to be explored before implementing real facilities. Aiming at that, the study profits by moving along the design cycle with standard steps.

The basic development stages for the design of instrumental robots, Fig. 7.11, require clear visibility on both the material resources (CFC frame) and on the logic resources (MDM frame) properties. On these premises, effectiveness can be reached by iterating the design cycle, Fig. 7.1, with due account of a few simple suggestions. Dynamics shaping and control planning are steps directly faced to achieve high robot performance by conventional setups. The availability of a library of control modules makes it easy to characterize the dynamic behavior in competing running conditions. The library SIRIxx includes common and sophisticated schemes; it can be generally used for control planning operations and as specialized aid for performing dynamics shaping. Of course the dynamic modelization implies knowledge about all links' centroids and mass quadratic moments; these parameters might be measured or experimentally identified, when actual robots are already available; alternatively, they are evaluated with the help of a solid modeler (interfaced to the SIRIxx package), at the earlier robot design or development stages. The inertial coupling is seldom considered by existing manufacturers of robotic equipment; such effects may be liable, however, of serious consequences on actual performance, since they introduce task modulation on the feedback gains; dynamics shaping, thus, is expected to become an important feature for advanced robotics, as dexterity and accuracy must be joined to high speed requests.

The function modulation aspects are commented in the Section 7.2 and expounded in Section 7.4, considering example cases: dynamics inconsistencies induced by coupling inertial effects; accuracy upgrading by the redesign of a fixtured wrist; dexterity improvement by redundant force control; versatility expansion by expert steering. The latter cases introduce the opportunities given by further sophistication; this is a step ahead in terms of sophistication and the option needs to be carefully evaluated to assess the return on investment. In the Section 7.3, concepts are reviewed by addressing the operation redundancy as a re-engineering issue to obtain process-attuned robots. The job can be grounded on standard rules by exploiting modularity, against the proper classification of the activity modes and the distinct presetting of the functional units. When the application area grants return (e.g., in micro-dynamics), the sophistication leads to mobility redundancy (cooperating robots) and command redundancy (position and force control).

Section 7.5 is devoted to these advanced developments of robotics with attention on manufacturing applications. The basic motivations of using robots with cooperation for automatic precision deburring is discussed, with hints on the machining process to show how the 'external' conditions are faced by manual workers and how a cooperating fixture might automatize the operations (with steady quality issue). The functional redundancy appears as a worthy opportunity, also, for assembly tasks, particularly to join highly compliant pieces or in front of micro-handling cases. All these situations require properly sophisticated models of the rigs dynamics, so that the design choices might be, step by step, validated with virtual reality simulation, before moving to the implementation of real fixtures.

Acknowledgments

We gratefully acknowledge the financial support of CNR (Italian Research Council) for the basic developments of these studies leading to the implementation of series of SIRIXX packages, under the frame of the project PFR (Progetto Finalizzato Robotica). We also thank the manufacturing companies that cooperated with us for the different developments, particularly: COMAU Robotica (Beinasco, Torino) and Speroni S.p.A. (Spessa, Pavia).

References

[AAC94] G.M. Acaccia, C. Aiachini, M. Callegari, R.C. Michelini, R.M. Molfino. 1994. Dynamics shaping for the control of instrumental robots, *Proc. 10th ISPE/IFAC Intl. Conf. on CAD/CAM, Robotics and Factories of the Future: CARs & FOF '94,* Ottawa, Aug. 21–24. 514–520.

[ACC93] G.M. Acaccia, M. Callegari, R. Caracciolo, R.C. Michelini, R.M. Molfino, M. Torbidoni. 1993. Redundant position/force control for advanced robot applications, *Advances in Computer Cybernetics and Information Engineering,* George E. Lasker, Ed. (The International Institute for Advanced Studies in Systems Research and Cybernetics Publ., Windsor, CA). 63–72.

[ACC94a] G.M. Acaccia, P.C. Cagetti, M. Callegari, R.C. Michelini, R.M. Molfino. 1994. Contact mechanics description of robot engagement tasks, *Proc. IASTED Intl. Conf. Applied Modelling and Simulation:* AMS '94, Lugano, Jun. 22–24. 32–35.

[ACC94b] G.M. Acaccia, P.C. Cagetti, M. Callegari, R.C. Michelini, R.M. Molfino. 1994. Modelling the impact dynamics of robotic manipulators, *Preprints 4th IFAC Symp. on Robot Control: SY.RO.CO. '94,* Capri, Sept. 19–21. 559–564.

[ACC94c] G.M. Acaccia, P.C. Cagetti, M. Callegari, R.C. Michelini, R.M. Molfino. 1994. Dynamic model of a robotised fixture for co-operative deburring operations, *Proc. 2nd European Solid Mechanics Conference: EUROMECH' 94,* Genova, Sept. 12–16.

[ACC95] G.M. Acaccia, M. Callegari, L. Consano, R.C. Michelini, R.M. Molfino, S. Pampagnin, R.P. Razzoli. 1995. Universal master for remote micro-manipulation, *Proc. First ECPD Int. Conf. on Advanced Robotics and Intelligent Automation,* Athens, Sept. 6–8. 499–504.

[ACH95] G.M. Acaccia, M. Callegari, D. Hagemann, R.C. Michelini, R.M. Molfino, S. Pampagnin, R. Razzoli, H. Schwenke. 1995. Robotic fixture for experimenting antropomorphic vision, *Proc. 7th Intl. Conf. on Advanced Robotics: ICAR '95,* Sant Feliu de Guìxols, Sept. 20–22. 237–244.

[ACM86] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino. 1986. Architectural analysis of robotic industrial manipulators, *Proc. AFCET/IASTED Intl. Symp. on Robotics and Artificial Intelligence,* Toulouse, Jun. 18–20. 579–598.

[ACM88] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino, P.A. Piaggio. 1988. X-ARS: a consultation program for selecting the industrial robot architectures, *Artificial Intelligence in Engineering: Robotics and Processes,* J.S. Gero Ed. (Elsevier Publ., Bath, UK). 35–58.

[ACM91a] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino, M. Recine. 1991. Functional coordination of multirobot equipment, *Proc. 14th IASTED Intl. Symp. Manufacturing and Robotics,* Lugano, Jun. 25–27. 122–125.

[ACM91b] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino, M. Recine. 1991. SIRIxx: a simulation programming environment for the design and the management of industrial robots, *Atti Convegno ANIPLA,* Milano, 29–30 ott. 461–474.

[ACM93] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino. 1993. Dynamic control of robots, *Proc. 3rd Intl. Symp. on Measurement and Control in Robotics: ISMCR '93,* Turin, Sept. 21–24, 1993. Bs.I-13:Bs.I–18.

[ACM95] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino, R. Razzoli. 1995. Dynamics of a multi-powered platform for task-steered instrumental robots, *Proc. IX World Congress on the Theory of Machines and Mechanisms,* Milano, Aug. 30–31/Sept. 1–2. 1816–1820.

[ACM96a] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino. 1996. The impact dynamics of robotic arms, *Proc. 2nd ECPD Int. Conf. on Advanced Robotics, Intelligent Automation and Active Systems,* Vienna, Sept. 26–28. 313–320.

[ACM96b] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino. 1996. Innovations in instrumental robotics: concurrency operations and co-operation, redundancy modulation and control, *Proc. 27th Intl. Symp. on Industrial Robots: ISIR '96,* Milano, Oct. 6–8. 37–42.

[ACM96c] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino, R.P. Razzoli. 1996. Assessing the dynamics of articulated manipulators with closed kinematic chains, *Proc. 27th Intl. Symp. on Industrial Robots: ISIR '96,* Milano, Oct. 6–8, 1996. 575–580.

[ACM96d] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino, R.P. Razzoli. 1996. The design of robotic equipment for flexible automation, *Proc. 2nd ECPD Int. Conf. on Advanced Robotics, Intelligent Automation and Active Systems,* Vienna, Austria, Sept. 26–28. 554–559.

[ACM96e] G.M. Acaccia, M. Callegari, R.C. Michelini, R.M. Molfino. Simulational assessment of a modular assembly facility. 1996. *Proc. Intl. Conf. on Concurrent Engineering and Electronic Design Automation: CEE '96,* Robinson College, Cambridge, Apr. 10–12. 37–41.

[ADA89] E.W. Aboaf, S.M. Drucker, C.G. Atkeson. 1989. Task-level robot learning; juggling a tennis ball more accurately, *Proc. IEEE Int. Conf. on Robotics and Automation,*. XXX. 1290–1295.

[Alg97] E.A. AlGallaf. 1997. Manipulation of ill-conditioned configurations by a robot hand: employment at local and global dexterities, *Mechatronics,* 7(5): 479–503.

[AMM84a] G.M. Acaccia, R.C. Michelini, R.M. Molfino, P.A. Piaggio. 1984. Simulation of adaptive controlling strategies for industrial robots, *Proc. Intl. Symp. Applied Modelling and Simulation,* Nice, 19–21 June.

[AMM84b] G.M. Acaccia, R.C. Michelini, R.M. Molfino. 1984. Computer-aided design procedures for the design of industrial robots: on-line generation of the dynamics equations, *Proc. Intl. Symp. Computer Aided Design,* Nice, Jun. 19–21. 183–187.

[AMM87] G.M. Acaccia, R.C. Michelini, R.M. Molfino. 1987. Development of CAD codes for the job integration of industrial robots, *Intl. J. Robotics,* 3(3/4): 371–388.

[AMM90] G.M. Acaccia, R.C. Michelini, R.M. Molfino, M.A. Recine. 1990. Simulational programming environment for the development of industrial multirobot systems, *Proc. ISCIE-ASME Symp. on Flexible Automation,* Kyoto, Jul. 9–12. 849–855.

[AMM91a] G.M. Acaccia, R.C. Michelini, R.M. Molfino, M.A. Recine. 1991. Assessment of position/force dynamic control performances for advanced robotics, *Proc. 5th Intl. Conf Advanced Robotics,* Pisa, Jun. 19–22. 1465–1468.

[AMM91b]G.M. Acaccia, R.C. Michelini, R.M. Molfino, M.A. Recine. 1991. Information reference setup for the development of industrial multirobot systems, *Intl. J. Computer Applications in Technology,* 4(3): 137–148.

[AMM91c] G.M. Acaccia, R.C. Michelini, R.M. Molfino, M.A. Recine. 1991. Modeling the coordination of multi-robot equipment, *Proc. 6th Intl. Conf. CAD/CAM, Robotics and Factories of the Future,* London, Aug. 19–22. 870–876.

[AMP89] H. Asada, Z.D. Ma, J.H. Park. 1989. Inverse dynamics of flexible robot arms: feasible solutions and arm design guidelines, *Proc. ASME Winter Meting, Robotics Research,* ASME DSC-Vol. 14. 279–287.

[AnH89] C.H. An, J.M. Hollerbach. 1989. The role of dynamic models in cartesian force control of manipulators, *Intl. J. of Robotics Research ,* **8**(4). 51–72.

[Ara83] S. Aramaki. 1983. Flexible playback control of an artificial hand, *Trans. Society of Instrument and Control Engineer.* **19** (6).

[Ard87] D.D. Ardayfio. 1987. *Fundamentals of Robotics,* Marcel Dekker Inc., New York, 1987.

[ArM83] S. Arimoto, F. Miyazaki. 1983. Stability and robustness of P.I.D. feedback control for robot manipulators of sensory capability, *Proc. 1st Int. Symp. Robotics Research.*

[AsA88] H. Asada, Y. Asari. 1988. The direct teaching of tool manipulation skills via impedance identification of human motions, *Proc. IEEE Int. Conf. on Robotics and Automation.* 1269–1274.

[Asd83] H. Asada. 1983. A geometrical representation of manipulator dynamics and its application to arm design, *ASME J. Dynamic Systems, Measurement and Control,* **105**. 131–1335.

[AsH79] H. Asada, H. Hanafusa. 1979. Playback control of force teached robots, *Trans. Society of Instrument and Control Engineers.* **15**(3).

[AsH89] H. Asada, S. Hirai. 1989. Towards a symbolic-level force feedback recognition of assembly process states, *Proc. 5th Int. Symp. of Robotic Research,* Tokyo.

[AsI89] H. Asada, H. Izumi. 1989. Automatic program generation from teaching data for the hybrid control of robots, *IEEE Trans. on Robotics and Automation,* **5**(2): 163–173.

[AsS86] H. Asada, J.J.E. Slotine. 1986. *Robotic Analysis and Control,* John Wiley Inc., New York, NY.

[AsT96] N. Asakawa, Y. Takeuch. 1996. Automatic deburring of cast iron workpiece: removal of projection on a convex sculptured surface, *Proc. 3rd Japan-France Congress on Mechatronics,* Besancon. 686–690.

[AsY87] H. Asada, K. Youcef-Toumi. 1987. *Direct-Drive Robots: Theory and Practice,* The MIT Press, Mass.

[AsY89] H. Asada, H., B.-H. Yang. 1989. Skill acquisition from human expert through pattern processing of teaching data, *Proc. IEEE Int. Conf. on Robotics and Automation.* 1302–1307.

[BAL91] D.F. Baldwin, T.E. Abell, M.C. Lui, T.L. De Fazio, D.E. Whitney. 1991. An integrated computer aid for generating and evaluating assembly sequences for mechanical products, *IEEE J. Robotics and Automation,* **7**(1): 78–94.

[BCQ86] M.A. Bronez, M.M. Clark, R. Quinn. 1986. Requirements development for a free-flying robot: the ROBIN, *Proc. IEEE Int. Conf. on Robotics and Automation.* 667–672.

[BEL91] G.M. Bone, M.A. Elbestawi, R. Lingarkar, L. Liu. 1991. Force control for robotic deburring, *ASME J. Dynamic Systems, Meas. and Control.***113** (3): 395–400.

[Ben97] D. Benarieh. 1997. Task management in a multi-robot environment, *Computer Integrated Manufacturing Systems.* **10**(2): 123–131.

[BeP90] W.K. Belvin, K.C. Park. 1990. Structural tailoring and feedback control synthesis: an interdisciplinary approach, *J. of Guidance, Control, and Dynamics.* **13**(3): 424–429.

[BeP97] N.P. Belfiore, E. Pennestri. 1997. An atlas of linkage-type robotic grippers, *Mechanism and Machine Design.* **32**(7): 811–833.

[BMM85] F. Bonsignorio, R.C. Michelini, R.M. Molfino, P.A. Piaggio. 1985. Polynomial control for assembly robots, *Proc. Vll Intl. Symp. Robotics & Automation,* Lugano, Jun. 24–26.

[BoJ85] D.S. Bodden, J.L. Junkins. 1985. Eigenvalue optimization algorithms for structure/controller design iterations, *J. of Guidance, Control, and Dynamics.* **8**(6): 697–706.

[BZL89] B. Benhabib, G. Zak, M.G. Lipton. 1989. A generalized kinematic modeling method for modular robots, *J. of Robotic Systems.* **6**(5): 545–571.

[CaB97] C. Canudas DeWit, B. Brogliato. 1997. Direct adaptive impedance control, *Automatica.* **33**(4): 643–654.

[CBZ90] R. Cohen, B. Benhabib, G. Zak. 1990. Kinematic modeling of modular robots with non-parallel and near-parallel axes units, *Proc. ASME Mechanisms Conference,* DE-Vol. 25, Chicago, Sept. 147–152.

[CCS91] P. Chiacchio, S. Chiaverini, L. Sciavicco, B. Siciliano. 1991. Task space dynamic analysis of multiarm system configurations. *Intl. J. of Robotics Research,* **10**(6): 708–715.

[CDM96] M. Callegari, F. Drago, R.M. Molfino, F. Principe, D. Speroni. 1996. High repeatability active vision wrist for 3D shapes measurements, *Proc. 27th Intl. Symp. on Industrial Robots,* Milano, Oct. 6–8. 347–352.

[ChL97] J.H. Chin, S.T. Lin. 1997. The path pre-compensation method for flexible arm robot, *J. Robotics and Computer Integrated Manufacturing.* **13**(3): 203–215.

[CLD92] R. Cohen, M.G. Lipton, M.Q. Dai, B. Benhabib. 1992. Conceptual design of a modular robot, *ASME J. Dynamic Systems, Measurement and Control.* **114.** 117–125.

[CMP94] P. Cagetti, R.C. Michelini, F. Pampagnin, R. Razzoli. 1994. SIRIAT: an animation module for virtual reality simulation of robotic manipulators, *Proc. 27th ISATA on Mechatronics,* Aachen, Oct. 31–Nov. 4. 609–616.

[CPP96] P.H. Chang, B.S. Park, K.C. Park. 1996. An Experimental Study on Improving Hybrid Position/Force Control of a Robot Using Time Delay Control. *Mechatronics.* 6(8): 915–931.

[Cra89] J.J. Craig. 1989. *Introduction to Robotics: Mechanics & Control,* Addison Wesley, Reading.

[DeL87] J. DeSchutter, J. Leysen. 1987. Tracking in compliant motion automatic generation of the task frame trajectory based on observation natural constraints, *Proc. 4th Int. of Robotics Research.* 215–22.

[DeS89] C.W. DeSilva. 1989. *Control Sensors and Actuators,* Prentice Hall Inc., New Yersey.

[Des96] R.M. DeSantis. 1996. Motion/Force Control of Robotic Manipulators. *ASME J. Dynamic Systems, Measurement and Control,* **118**(2): 386–389.

[Dra77] S.H. Drake. 1977. Using compliance in lieu of sensory feedback for automatic assembly, *Proc. IFAC Symp. on Information and Control Problems in Manufacturing Technology,* Tokyo.

[ESG90] S.D. Eppinger, R.P. Smith, D.A. Gebala, D.E. Whitney. 1990. Organizing the tasks in complex design projects, *Proc. ASME Design Automation Conference: Design Theory and Methodology,* Vol. DE–27, Chicago, Sept. 39–46.

[FaH97] Y. Fang, Z. Huang. 1997. Kinematics of a three-degrees-of-freedom in-parallel actuated manipulator mechanism, *Mechanism and Machine Design.* **32**(7): 789–796.

[Fer66] W.R. Ferrell. 1996. Delayed force feedback, *Human Factors*. 449–455.

[FFM97] L. Ferrarini, G. Ferretti, C. Maffezzoni, G. Magnani. 1997. Hybrid Modeling and Simulation for the Design of an Advanced Industrial Robot Controller. *IEEE Robotics & Automation Magazine.* **4**(2): 45–51.

[FGL87] K.S. Lu, R.C. Gonzales, C.S.G. Lee. 1987. *Robotics: Control, Sensing, Vision and Intelligence.* McGraw-Hill, New York, NY.

[FiM92] W.D. Fisher, M.S. Mujtaba. 1992. Hybrid position/force control: a correct formulation. *Intl. J. of Robotics Research,* **11**(4): 299–311.

[FWY86] S. Fortune, G. Wilfgong, C. Yap. 1986. Coordinated motion of two robot arms, *Proc. IEEE Int. Conf. on Robotics and Automation,* San Francisco, Apr. 7–10. 1216–1223.

[GHW83] R.E. Gustavson, M.J. Hennessey, D.E. Whitney. 1983. Designing chamfers, *Robotics Research.* **2** (4): 3–18.

[GKY84] S.D.V. Gruzdev, O.B. Korytko, E.I. Yurevich. 1984. Modular electro-mechanical industrial robots, *Elektroteknika.* **55** (4): 4–7.

[GrM61] D. Graham, D. McRuer. 1961. *Analysis of Non-Linear Control Systems,* John Wiley, New York.

[GrR88] S.C. Graves, C.H. Redfield. 1988. Equipment selection and task assignment for multiproduct assembly system design, *Int. J. of Flexible Mfr. Sys.* **1**: 31–50.

[Gus88] R.E. Gustavson. 1988. Design of cost-effective assembly systems, *Proc. Successfully Planning and Implementation of Flexible Assembly Systems,* SME, Mar., Ann Arbor, MI.

[HaA77] H. Hanafusa, H. Asada. 1977. A robotic hand with elastic finger and its application to assembly processes, *Proc. IFAC Symp. on Information Control Problems in Production Engineering,* 127–138.

[HaN89] A.M.A. Hamdan, A.H. Nayfeh. 1989. Measure of modal controllability and observability for first- and second-order linear systems, *J. of Guidance, Control, and Dynamics.* **12**(3): 421–428.

[HeK91] M.G. Herr, H. Kazerooni. 1991. Automated robotic deburring of parts using compliance control, *ASME J. Dynamic Systems, Meas. and Control.* **113**(1): 60–66.

[Hic85] P.K. Hickman. 1985. An Analysis of Burrs and Burr Removal on Aircraft Engine Parts. SB Thesis. MIT.

[HiH83] G. Hirzinger, J. Heindl. 1983. Sensor programming: a new way for teaching robot parts and forces/torques simultaneously, *Proc. 3rd Int. Conf. on Robot Vision and Sensory Controls.* 549–558.

[HiL85] G. Hirzinger, K. Landzettel. 1985. Sensory feedback structures for robots with supervised learning, *Proc. IEEE Int. Conf. on Robotics and Automation.* 627–635.

[HKS92] T. Hamilton, A. Kondoleon, D. Seltzer. 1992. Automation of inertial instruments, C.S. Draper Lab report P-3190, *Presented at Joint Services Data Exchange for GN&C,* Palm Springs, Oct.

[Hog79] N. Hogan. 1979. Adaptive stiffness control in human movement, *ASME J. Advances in Bioengineering,* 53–54.

[Hog80] N. Hogan. 1990. Control of mechanical impedance of prosthetic arms, *Proc. JACC.*

[Hog81] N. Hogan. 1981. Impedance control of a robotic manipulator, *Winter Annual Meeting of the ASME,* Washington.

[Hog85] N. Hogan. 1985. Impedance control: an approach to manipulation, Part I-III, *ASME J. Dynamic Systems, Measurement, and Control.* **107**(1): 1–23.

[HoG87] R. Hollowell, R. Guile. 1987. An analysis of robotic chamfering and deburring, *ASME Winter Annual Meeting: Robotics Theory and Applications*.

[HuJ86] S.S. Hussaini, D.E. Jakopac. 1986. Multiple manipulators and robotic workcell coordination, *Proc. IEEE Int. Conf. on Robotics and Automation,* San Francisco, Apr. 7–10. 1236–1241.

[HWM86] R. Harrison, R.H. Weston, P.R. Moore, T.W. Thatcher. 1986. Industrial applications of pneumatic servo-controlled modular robots, *Proc. 1st National Conf. on Production research* (*U.K.*). 229–236.

[IOY94] M. Ichinohe, K. Ohara, K. Yamaguchi, K. Maeda. 1994. Development of deburring robot for cast iron with vision and force sensing, *Proc. 24th Intl. Symp. on Industrial Robots*. 49–54.

[IYI96] S. Ito, H. Yuasa, K. Ito, M. Ito. Energy-based pattern transition in quadrupedal locomotion with oscillator and mechanical model, *Proc. Intl. IEEE Conf. Man and Cybernetics,* Beijing. 2321–2326.

[Jen86] L.M. Jenkins. 1986. Telerobotic work system: space robotics applications, *Proc. IEEE Int. Conf. on Robotics and Automation.* 804–806.

[JKL97] H.E. Jenkins, T.R. Kurfess, S.J. Ludwick. 1997. Determination of a dynamic grinding model. *ASME J. Dynamic Systems, Measurement and Control,* **119**(2): 289–293.

[Jok97] T.A.E. Jo Ko. 1997. A dynamic surface roughness model for face milling, *Precision Engineering,* **20**(3): 171–178.

[KAG96] M. Katayama, K. Asada, X.Z. Zheng, M. Yamakita, K. Ito. 1996. Self-organisation of a task oriented visuo-motor map for a redundant arm, *Proc. IEEE Conf. Emerging Technologies and Factory Automation,* Hawaii. 302–308.

[Kam83] L.J. Kamm. 1983. Recent applications of modular technology robots, *Proc.,13th Int. Symp. on Industrial Robots.* 11.66–11.74.

[Kaz87] H. Kazerooni. 1987. Automated robotic deburring using electronic compliance impedance control, *Proc. IEEE Intl. Conf. on Robotics and Automation,* Raleigh, USA, Mar. 31-Apr. 3. 1025–1032.

[Kaz89] H. Kazerooni. 1989. On the Robot Compliant Motion Control. *ASME J. Dynamic Systems, Measurement and Control,* **111**(3): 416–425.

[KBK86] H. Kazerooni, J.J. Bausch, B.M. Kramer. 1986. An approach to automated deburring by robot manipulators, *ASME J. Dynamic Systems, Meas. and Control.* **108**(4): 354–359.

[KeK88] L. Kelmar, P.K. Khosla. 1988. Automatic generation of kinematics for a reconfigurable modular manipulator system, *IEEE Proc. Int. Conf. on Robotics and Automation.* 663–668.

[KHB92] W.S. Kim, B. Hannaford, A. Bejczy. 1992. Force reflection and shared compliant control in operating telemanipulators with time delay, *IEEE Trans. Robotics & Automation,* **8**(2): 176–185.

[KiH86] R. King, R. Hahn. 1986. *Handbook of Modern Grinding Technology.* 34–38.

[KIK90] O. Kashiwagi, K. Ono, E. Izumi, T. Kurenuwa, K. Yamada. 1990. Force-controlled robot for grinding, *IEEE Int. Workshop on Intelligent Robots and Systems.* 1001–1006.

[KiT97] S. Kirk, E. Tebaldi. 1997. Design of robotic facilities for agile automobile manufacturing. *Industrial Robot.* **24**(1): 72–77.

[KKM90] R.L. Kosut, G.M. Kabuli, S. Morrison, Y.P. Harn. 1990. Simultaneous control and structure design for large space structures, *Proc. American Control Conference.* 860–865.

[KKN95] A. Kato, N. Kondo, N. Narita, K. Ito, Z.W. Luo. 1995. Compliance control of direct drive manipulator using ultrasonic motor, *Theory and Practice of Robots and Manipulators.* 125–130.

[Koi89] A.J. Koivo. 1989. *Fundamentals for Control of Robotic Manipulators,* John Wiley, New York, NY.

[Kov97] J. Kovecses. 1997. Joint motion dynamics and reaction forces in flexible link robotic mechanism, *Mechanism and Machine Design.* **32**(7): 869–880.

[KuW92] T.R. Kurfess, D.E. Whitney. 1992. Predictive control of a robotic grinding system. *ASME J. Dynamic Systems, Measurement and Control,* **114**(4): 412–420.

[KWB88] T.R. Kurfess, D.E. Whitney, M.L. Brown. 1988. Verification of a dynamic grinding model, *ASME J. Dynamic Systems, Meas. and Control.* **110**(4): 403–409.

[LAM88] H.G. Lee, S. Arimoto, F. Miyazaki. 1988. Liapunov stability analysis for PDS control of flexible multi–link manipulators, *Proc. 27th Conf. on Decision and Control.* 75–80.

[LBH89] D.K. Lindner, J. Babendreier, A.M.A. Hamdan. 1989. Measure of controllability, observability and residues, *IEEE Trans. Automatic Control,* **34**(6): 648–650.

[LeR87] G. Legnani, R. Riva. 1987. Kinematics of modular robots, *Proc. World Congress on Mechanisms and Machine Theory,* Spain. 1159–1162.

[Li97] Y. Li. 1997. Hybrid control approach to the peg-in-hole problem. *IEEE Robotics & Automation Magazine.* **4**(2): 52–60.
[LiA92] S. Liu, H. Asada. 1992. Transferring manipulative skills to robots: representation and acquisition of tool manipulative skills using a process dynamics model. *ASME J. Dynamic Systems, Measurement and Control,* **114**(2): 220–228.
[LiG93] K.B. Lim, W. Gawronski. 1993. Actuator and sensor placement for control of flexible structures, *Control and Dynamic Systems: Advances in Theory and Applications,* C.T. Leondes Ed., Academic Press.
[LII96a] Z.W. Luo, K. Ito, M. Ito, A. Kato. 1996. Dynamic co-operative manipulation of flexible objects, *Japan-USA Symp. Flexible Automation,* Boston. 229–232.
[LII96b] B.L. Lu, K. Ito, M. Ito. 1996. Solving inverse kinematics problems of redundant manipulators in an environment with obstacles, using separable nonlinear programming, *Proc. Japan-USA Symp. Flexible Automation,* Boston. 79–82.
[LII96c] Z.W. Luo, K. Ito, M. Ito, A. Kato. 1996. On co-operative manipulation of dynamic objects, *J. Advanced Robotics.* **10**(6): 621–636.
[LiJ89] K.B. Lim, J.L. Junkins. 1989. Robust optimization of structural and controller parameters, *J. of Guidance, Control, and Dynamics.* **12**(1): 89–96.
[LIK96] Z.W. Luo, M. Ito, A. Kato, K. Ito. 1996. Nonlinear robust control for compliant manipulation on dynamic environment, *J. Advanced Robotics.* **10**(2): 213–227.
[LuI96] B.L. Lu, K. Ito. 1996. A parallel and modular multi-sieving neural network architecture with multiple control networks, *Proc. Intl. IEEE Conf. Man and Cybernetics,* Beijing. 1303–1308.
[LWP80] J.Y.S. Luh, M.W. Walker, P.R. Paul. 1980. On-line computational scheme for mechanical manipulators, *ASME J. of Dynamic Systems, Measurement and Control.* **102**: 69–76.
[LYK97] S.H. Lee, B.J. Yi, Y.K. Kwak. 1997. Optimal kinematic design of an anthropomorphic robot module with redundant actuators, *Mechatronics.* **7**(5): 443–464.
[MAC93] R.C. Michelini, G.M. Acaccia, M. Callegari, R.M. Molfino. 1993. Virtual reality technique for the development and integration of robotic manipulators, *Proc. 9th Intl. Conf. on CAD/CAM, Robotics and Factories of the Future,* St. Petersburg, May 17–20. 425–430.
[MaC96] L. Markov, R.M.H. Cheng. 1996. Conceptual design of robotic filament winding complexes. *Mechatronics.* **6**(8): 881–896.
[MAC97] R.C. Michelini, G.M. Acaccia, M. Callegari, R.M. Molfino, R.P. Razzoli. 1997. Dynamics of a cooperating robotic fixture for supporting automatic deburring tasks, *Proc. Intl. Conf. Informatics and Control,* St. Petersburg, Jun. 9–13, 1244–1254.
[MAC98] R.C. Michelini, G.M. Acaccia, M. Callegari, R.M. Molfino, R.P. Razzoli. 1998. Techniques in computer integrated assembly for cost effective developments, in *Computer Aided and Integrated Manufacturing Systems Techniques and Applications,* Cornelius T. Leondes, Ed., Gordon & Breach Publ., Newark, NJ, 1998.
[Mak80] H. Makino. 1980. Research and development of the SCARA robot, *Proc. 4th Intl. Conf. on Production Engineering,* Tokyo, Japan Society of Precision Engineering. 885–890.
[MaR89] T. Marilier, J.A. Richard. 1989. Non-linear mechanic and electronic behavior of a robot axis with a harmonic drive gear, *J. of Robotics and Integrated Manufacturing.* **213**(5): 129–136.
[McK91] P.J. McKerrow. 1991. *Introduction to Robotics.* Addison-Wesley, Sydney.
[MCR96] R.C. Michelini, M. Callegari, G.B. Rossi. Robots with uncertainty and intelligent automation, *Proc. 2nd ECPD Int. Conf. on Advanced Robotics, Intelligent Automation and Active Systems,* Vienna, Sept. 26–28. 31–39.
[MHS97] B.J. McCarragher, G. Hovland, P. Sikka, P. Aigner, D. Austin. 1997. Hybrid dynamic modeling and control of constrained manipulation systems. *IEEE Robotics & Automation Magazine.* **4**(2): 27–44.
[Mic92] R.C. Michelini. 1992. Decision anthropocentric manifold in robotic manufacturing, *Proc. 4th ASME Intl. Symp. on Flexible Automation,* San Francisco, USA, Jul. 12–15. 467–474.

[MiI96] J.K. Mills, J.G.-L. Ing. 1996. Dynamic modeling and control of a multi-robot system for assembly of flexible payloads with applications to automotive body assembly. *J. Robotic Systems.* **13**(12): 817–836.

[Mil96] J.K. Mills. 1996. Simultaneous control of robot manipulator impedance and generalized force and position. *Mechanisms and Machine Theory.* **31**(8): 1069–1080.

[MiS87] D.F. Miller, J. Shim. 1987. Gradient-based combined structural and control optimization, *J. of Guidance, Control, and Dynamics,* **10**(3)

[MMA83] R.C. Michelini, R.M. Molfino, G.M. Acaccia. 1983. The development of modular simulation procedures for the design of task-dependant industrial robots, *Proc. Intl. Symp. Robotics & Automation,* Lugano, Jun. 22–24.

[MPM78] R.C. Michelini, P.L. Polledro, C. Marcantoni Taddei. 1978. Position steering of industrial robots by statistical controllers, *Proc. 8th Intl. Symp. on Industrial Robots* Stuttgart, May 31–Jun. 1.

[MuM84] R. Muck, J.A.G. Mammern. 1984. Modular mechanical engineering, IFS, *Proc. Int. Conf. on Advances in Manufacturing.* 271–282.

[MuP97] P. Muraca, P. Pugliese. 1997. A variable structure regulator for robotics, *Automatica,* **33**(7): 1423–1426.

[NeW78] J.L. Nevins, D.E. Whitney. 1978. Computer controlled assembly, *Scientific American,* **238**(2): 62–74.

[Nil69] N. Nilsson. 1969. A mobile automation: an application of artificial intelligence techniques, *Proc. Int. Joint Conf. on Artificial Intelligence*. 509–520.

[NoH89] S.Y. Nof, D. Hanna. 1989. Operational characteristics of multi-robot systems with cooperation, *Intl. J. Production Researches.* **27**(3)

[NWD89] J.L. Nevins, D.E. Whitney, T.L. De Fazio, R.E. Gustavson, A.C. Edsall, R.W. Metzinger, W.A. Dvorak. 1989. A strategy for the next generation in *Concurrent Design of Products and Processes in Manufacturing,* McGraw-Hill, New York, NY.

[OKA97] F. Ozturk, N. Kaya, O.B. Alankus, S. Sevinc. 1997. Machining features and algorithms for set-up planning and fixture design, *Computer-Integrated Manufacturing Systems.* **9**(4): 207–216.

[PaA91] J.H. Park, H. Asada. 1991. Dynamic analysis of noncollocated flexible arms and design of torque transmission mechanisms, *Proc. American Control Conference.* 1885–1890.

[PaA94] J.H. Park, H. Asada. 1994. Concurrent design optimisation of mechanical structure and control for high speed robots, *ASME Trans. J. Dynamic Systems, Measurement and Control.* **116:** 244–256.

[Pau8] R.P. Paul. 1981. *Robot Manipulator: Mathematics, Programming, and Control,* The MIT Press, Mass.

[Pek64] J. Peklenik. 1964. Contributions to the theory of surface characterisation, *CIRP Annals.* **12**: 173–178.

[Pel96] M. Pelletier. 1996. Synthesis of hybrid impedance control strategies for robot manipulators. *ASME J. Dynamic Systems, Measurement and Control,* **118**(3): 566–571.

[PeV96] W. Persoons, P. Vanherck. 1996. A process model for robotics cup grinding, *CIRP Annals.* **45**(1): 319–325.

[RaC81] M.H. Raibert, J.J. Craig. 1981. Hybrid position/force control of manipulators, *ASME, J. of Dynamic Systems, Measurement and Control,* **102**(2): 126–133.

[Riv88] E.I. Rivin. 1988. *Mechanical Design of Robotics,* McGraw Hill, New York.

[RLC97] W.B. Rowe, Y. Li, X. Chen, B. Mills. 1997. Case-based reasoning for selection of grinding conditions, *Computer-Integrated Manufacturing Systems.* **9**(4): 197–205.

[ROB97] S. Reignier, F.B. Ouezdou, P. Bidaud. 1997. Distributed method for inverse kinematics of all-serial manipulators, *Mechanism and Machine Design.* **32**(7): 855–867.

[RoM66] R.A. Rothchild, R.W. Mann. 1966. An EMG controlled force sensing proportional rate elbow prosthesis, *Proc. Symp. on Biomedical Engineering,* Milwaukee.

[RoS92] A. Romiti, M. Sorli. 1992. A parallel 6 d.o.f. manipulator for cooperative work between robots in deburring, *Proc. 23rd Intl. Symp. on Industrial Robotics:*Barcelona. 437–442.

[SaK97] V. Santibanez, R. Kelly. 1997. Strict Lyapunov functions for control robotic manipulators, *Automatica.* **33**(4): 675–682.

[Sal80] J.K. Salisbury. 1980. Active stiffness control of a manipulator in cartesian coordinates, *Proc. 19th IEEE Conf. on Decision and Control.* Albuquerque

[She86] T. Sheridan. 1986. Merging mind and machine, *Technol. Rev.* **23**(7): 32–40.

[ShS84] V.I. Shub, M.K. Selder. 1984. Pneumatic modular industrial robots, *Elektrotekhnika.* **55**(4): 7–9.

[Sim75] S.N. Simunovic. 1975. Force information in assembly processes, *Proc. 5th Intal. Symposium on Industrial Robots,* Chicago, IL

[SmC82] R.C. Smith, K. Cazes. 1982. Modularity in robotics: technical aspects and applications, *IFS Proc., Int. Conf. on Robotics in the Automotive Industry* (*UK*). 115–122.

[SoC93] M. Sorli, M. Ceccarelli. 1993. On the workspace of a 6 d.o.f. platform with three articulated double-parallelograms. *Proc. Intl. Conf. on Advanced Robotics:* Tokyo. 147–152.

[SpF91] V.A. Spector, H. Flashner. 1991. Modeling and design implications of noncollocated control in flexible systems, *ASME J. Dynamic Systems, Measurement and Control.* **112**: 186–193.

[SSG87] T.M. Stepien, L. Sweet, M. Good, M. Tomizuka. 1987. Control of tool-workpiece contact force with application to robotic deburring, *IEEE Trans. on Robotics and Automation.* **3**.

[Ste81] D.V. Steward. 1981. The design structure matrix, *IEEE Trans. Eng. Mgt.,* **28**(3): 71–74.

[StS90] D.M. Stokic, D. Surdilovic. 1990. Simulation and control of robotic deburring, *Intl. J. of Robotics and Automation.* **5**(3): 107–114.

[TeB89] D. Tesar, M.S. Butler. 1989. A generalized modular architecture for robot structures, *ASME J. of Manufacturing Review.* **2**(2): 91–117.

[UIH87] M. Uchiyama, N. Iwasawa, K. Hakomori. 1987. Hybrid position/force control for the coordination of two-arms robot, *IEEE Conf. Robotics and Automation,* Raleigh, USA

[VaP96] H. VanBrussels, W. Persoons. 1996. Robotic deburring of small series of castings, *CIRP Annals,* **45**(1): 405–410.

[Ver83] S.A. Vere. 1983. Planning in time: windows and durations for activities and goals, *IEEE Trans. on Pattern Analysis and Machine Intelligence.* **5**(3): 246–266.

[VuK89] M. Vukobratovic, N. Kirkanski. 1989. *Real-Time Dynamics of Manipulation Robots,* Springer Verlag, New York, NY.

[WaD75] P.C. Watson, S.H. Drake. 1975. Pedestal and wrist force sensors for industrial assembly, *Proc. 5th Intl. Symposium on Industrial Robots,* Chicago, IL.

[Wat76] P.C. Watson. 1976. A multidimensional system analysis of the assembly process as performed by a manipulator, *Proc. 1st North American Robot Conference,* Chicago, IL.

[WET90] D.E. Whitney, A.C. Edsall, A.B. Todtenkopf, T.R. Kurfess, A.R. Tate. 1990. Development and control of an automated robotic weld bead grinding system, *ASME J. Dynamic Systems, Meas. and Control.* **112**(2): 166–176.

[Whi69a] D.E. Whitney. 1969. Resolved motion rate control of manipulators and human prostheses, *IEEE Trans. Man-Machine Systems.* **10**(2): 47–53.

[Whi69b] D.E. Whitney. 1969. State space models of remote manipulation tasks, *IEEE Trans. Automatic Control.* **14**(6): 617–623.

[Whi72] D.E. Whitney. 1972. Mathematics of coordinated control of prosthetic arms and remote manipulators, *ASME J. Dynamic Systems, Measurement and Control.* **93**(4): 303–309.

[Whi77] D.E. Whitney. 1977. Force feedback control of manipulator fine motions, *ASME Journal of Dynamic Systems, Measurement and Control.* **99**(2): 91–97.

[Whi82] D.E. Whitney. 1982. Quasi-static assembly of compliantly supported rigid parts, *ASME J. Dynamic Systems, Measurement and Control.* **104**: 65–77.

[Whi93] D.E. Whitney. 1993. From robots to design, *ASME Trans. J. Dynamic Systems, Measurement and Control.* **115**: 262–270.

[WhR86] D.E. Whitney, J.M. Rourke. 1986. Mechanical behavior and design equations for elastomer shear pad remote center compliances, *ASME Journal of Dynamic Systems, Measurement and Control.* **108**(3): 223–232.

[WhT92] D.E. Whitney, E.D. Tung. 1992. Robot grinding and finishing of cast iron stamping dies, *ASME J. Dynamic Systems, Measurement and Control.* **114**: 132–140.

[WKT90] D.E. Whitney, T.R. Kurfess, A.B. Todtenkopf, M.L. Brown, A.C. Edsall. 1990. Development and control of an automated robotic weld bead grinding system, *ASME J. Dynamic Systems, Measurement and Control.* **112**(2): 166–176.

[WLY96a] J.Q. Wu, Z.W. Luo, M. Yamakita, K. Ito. 1996. Adaptive hybrid control of manipulators on uncertain flexible objects, *J. Advanced Robotics.* **10**(5): 469–485.

[WLY96b] J.Q. Wu, Z.W. Luo, M. Yamakita, K. Ito. 1996. Gain scheduled control of robot manipulators for contct tasks on uncertain flexible objects, *Proc. Intl. IEEE Conf. Man and Cybernetics,* Beijing. 41–46.

[WLY96c] J.Q. Wu, Z.W. Luo, M. Yamakita, K. Ito. 1996. Adaptive hybrid control for a robot interacting with uncertain flexible environments, *13th IFAC World Congress,* San Francisco. 235–240.

[Wur86] K.H. Wurst. 1986. The conception and construction of a modular robot system, *IFS, Proc. Int. Symp. on Industrial Robotics,* Belgium. 37–44.

[YHM94] T. Yoshikawa, K. Harada, H. Murakami. 1994. Dynamic hybrid position/force control of flexible arms by macro-micro manipulator systems, *Proc. ISCIE-ASME Intl. Conf. Flexible Automation,* Jul. 11–18. 65–72.

[YLI96] M. Yamakita, Z.W. Luo, K. Ito. 1996. Potential field representation of environment model and its application to robot's force/position hybrid control, *Proc. Intl. IEEE Conf. Emerging Technologies and Factory Automation,* Hawaii. 316–321.

[Yos93] T. Yoshikawa. 1993. Dynamics shaping in robot force control and artificial reality, *Proc. Intl. Conf. on Advanced Robotics,* Tokyo. 3–8.

[YoZ93] T. Yoshikawa, X.-Z. Zheng. 1993. Coordinated dynamic hybrid position/force control for multi-robot manipulators handling one constrained object. *Intl. J. Robotics Research,* **12**(3): 219–230.

[ZLJ87] Y.F. Zheng, J.Y.S. Luh, P.F. Jia. 1987. A real time distributed computer system for coordinated motion control of two industrial robots, *IEEE Conf. Robotics and Automation,* Raleigh, USA.

[ZOY96a] X.Z. Zheng, K. Ono, M. Yamakita, M. Katayama, K. Ito. 1996. Trajectory planning and control for robotic batting/catching tasks, *Proc. Japan-USA Symp. Flexible Automation,* Boston. 17–23.

[ZOY96b] X.Z. Zheng, K. Ono, M. Yamakita, M. Katayama, K. Ito. 1996. A control structure for robotic dynamic manipulation, *Intl. IEEE Conf. Man and Cybernetics,* Beijing. 1489–1494.

[ZOY96c] X.Z. Zheng, K. Ono, M. Yamakita, M. Katayama, K. Ito. 1996. A robotic dynamic manipulation system with trajectory planning and control, *Intl. IEEE Conf. Emerging Technologies and Factory Automation,* Hawaii. 309–315.