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DESIGN OF ADVANCED ROBOTIC SYSTEMS FOR ASSEMBLY AUTOMATION

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Abstract: *The paper describes the architecture of the virtual prototyping environments that can be presently set up to try to make the best from a concurrent mechatronic design of mechanical devices and control systems: though a single comprehensive tool is not available on the market at the moment, a proper integration of different software modules can do the job. As an example, a hybrid kinematic architecture for mechanical assembly is presented, based on the functional splitting of complex tasks between two cooperating parallel kinematics machines with limited mobility and equipped by proper interaction control.*

Key words: *design automation, virtual Prototyping, mechatronics, automated assembly, robotics.*

1. CAD ENVIRONMENTS FOR MECHATRONIC DESIGN

The automation of assembly tasks has been studied extensively for a long time, but the accomplishment of effective processes still deserves further research efforts [1]: the opportunities offered by current state-of-the-art technology cannot sometimes be taken due to the complexity of the resulting plants, that makes difficult their design or even their management; this is the case, for instance, of assembly cells based on parallel kinematics machines.

Up-to-date design criteria deserve a tight integration between mechanics and control [2], according to the mechatronics paradigms shown in Fig. 1. The benefits of this approach are quite clear indeed: both shorter development times and a potential enhancement of system's performances can be easily achieved, since the design is not aimed at a "local" optimization of single modules (mechanics, electronics, informatics, etc.) but rather looks for suitable solutions for the entire system.

The use of this approach is much simplified by the availability of development environments able to support the designer during all the design steps [3], possibly up to the prototyping phase to be carried on with the aid of "hardware-in-the-loop" simulation tools. As a matter of fact, the need to reconsider previous design steps, that is pretty common in usual engineering practice by the way, is not dramatic in case an integrated development environment is available. Sometimes the same platform can also be used during the start-up and/or management of the plant itself, provided that the software tools support production planning activities, possibly up to off-line machines programming.

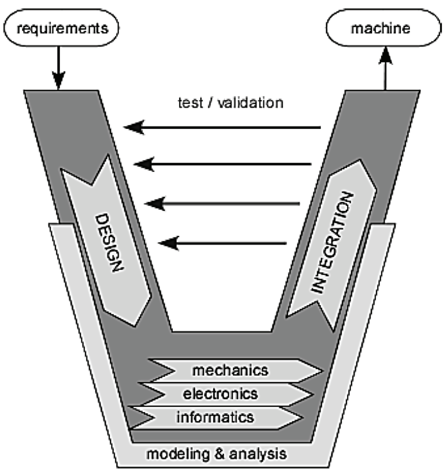

Fig. 1. V-model for the development of mechatronic systems (adapted from VDI 2206 standard, 2003 [4]).

Unfortunately a comprehensive design environment able to fulfill all the functions that have been outlined is not presently available in the market, in spite of providers' efforts to extend more and more the capabilities of their software packages. Therefore, it is now needed the use of different tools for the various aspects of the design and it is necessary to make resort to their capability to interface one to the other at various levels of integration, from the mere sharing of models that have been coded in proper file formats, to the synchronization of different processes, up to the full associativity of packages that can even share the same user interface.

2. ASSEMBLY MODELING

Fig. 2 shows the virtual prototyping environment that is used at the Department of Mechanics of the Polytechnic University of Marche for the design of automated assembly systems based on parallel kinematic manipulators. The mechanical design is developed through conventional CAD tools, that allow to easily define even the most complex geometries and also to perform, *e.g.*, by means of FEM modules, the needed structural analyses; the interface with a multibody code allows to perform a closed-loop dynamic analysis, with different levels of difficulty according to the associativity of the used programs. To this aim, the MSC VisualNastran code is often used but in most complex cases the LMS Virtual.Lab Motion package has been used too, which is able to handle in a more convenient way complex situations like, for

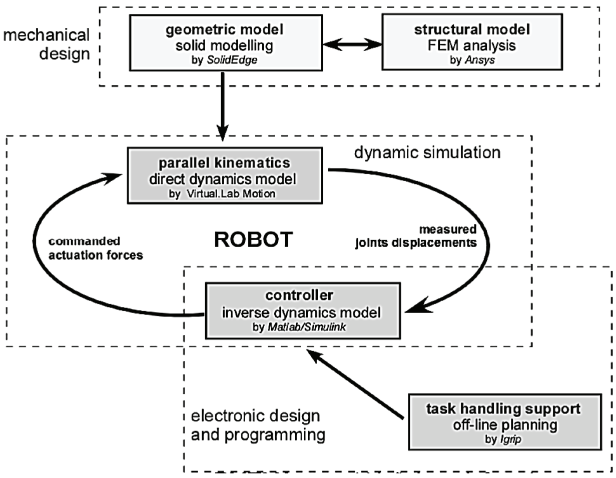

Fig. 2. Virtual prototyping environment for mechatronic design.

instance, the occurrence of an impact. In any case, the scheme of the simulation is always the same: the multibody code receives in input from the controller the actuation torques and integrates the equation of direct dynamics, providing in output the state variables that are assumed to be measured. The control system, which is implemented in the Matlab/Simulink environment, computes the control actions taking into account the assembly task to be executed and sometimes by exploiting the complete or partial knowledge of robot's dynamics (inverse dynamics model). If the task is constrained by the contact with the environment, like is usually the case for assembly, the contact forces can be measured too, to set up more efficient force control schemes.

As for task planning and robot programming, it is possible to use both commercial programs or specific packages, purposely developed for the application presently treated: a sample code developed for the planning of assembly tasks is shown in the next section; as for commercial packages, the Authors have experience of the Delmia IGRIP software that, once the task has been defined off-line, is able to generate the part program for the controllers of the most common robot manufacturers.

In the end, once the most appropriate control logics have been set up off-line, an advanced development environment should allow the direct generation of the code for the controller and its download to the actual control hardware.

3. ANALYSIS AND PLANNING OF ASSEMBLY TASKS

The usefulness of a computer aided support tool for the planning of assembly tasks can be effectively shown with reference to the well known case of peg-in-hole assembly: even in the simplest case of rigid bodies, cylindrical surfaces and smoothed chamfers, many variables affect the process, as for instance diametral play, misalignment angle, friction coefficient, contact forces and moments, etc.

In any case, an effective accomplishment of the task must be based on the availability of suitable compliant wrists or, in case a high accuracy is needed, on manipulator's capability of controlling both mutual positions and static and/or dynamic actions between the parts in contact. It is therefore easily understood that an impedance or even a hybrid position/force control is better designed only after a careful study of the parameters involved in the task.

By making reference to the classic studies developed by D.E. Whitney and J.L. Nevins at MIT in the first '80s [5–6], the so-called "fine motion" assembly has been divided into the following five phases, shown in Fig. 3: approach, chamfer crossing, one-point contact, two-points contact, linear contact and a specific Matlab code has been developed for the simulation and planning of the resulting scenarios.

Two typical problems can arise during the assembly task, both preventing the fulfilment of the operation because the peg appears stuck in the hole: the *jamming* consists in a wrong proportion among the exerted forces and moments and can occur both during one-point and two-point contact phases; the *wedging*, on the other hand, can arise only during the two-point contact phase and, deriving from a wrong geometric setting, cannot be avoided by varying the applied forces or moments.

The mathematical model of both situations has been derived and useful diagrams have been drawn [7]. Fig. 4,

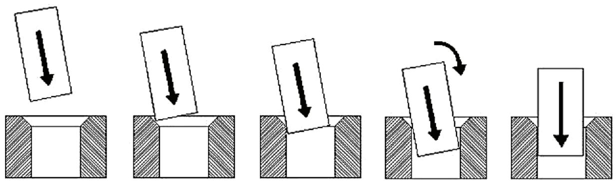

Fig. 3. The five different phases of fine-motion assembly.

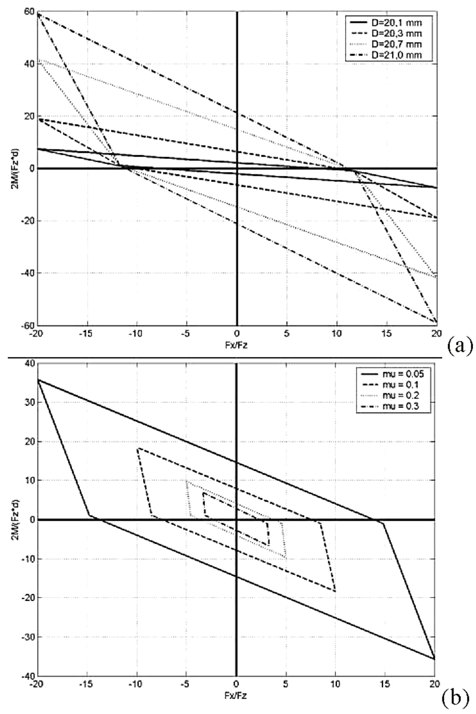

Fig. 4. Jamming diagram: a) for different values of hole's diameter D ($\mu = 0.05$, $d = 20.0$ mm, $\theta = 2°$); b) for different values of friction coefficient μ ($D = 20.3$ mm, $d = 20.0$ mm, $\theta = 1°$).

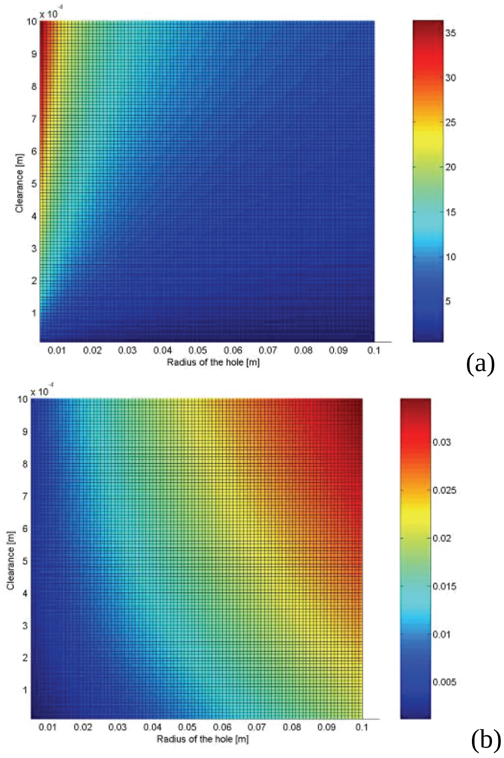

Fig. 5. Limit values for tilt angle (a) and insertion depth (b) to avoid wedging.

for instance, refers to a sample case characterised by peg's diameter *d*, hole's diameter *D*, static friction coefficient μ and parts' misalignment θ: some of these parameters are assigned while others are varied in order to study the sensitivity of the assembly to such variations (*e.g.*, diametral play in Fig. 4a or friction coefficient in Fig. 4b). The figures plot with lines of different style the combination of applied actions (lateral force F_x, axial thrust F_z and moment M_z) that correspond to situations of equilibrium: the inside area represents a slipping region where the dynamic unbalance among the external and the reaction forces leads to successful mating of the parts, while the region outside such equilibrium lines eventually jam the peg, either in one- or two-point contact.

In Fig. 5, moreover, the limit values of the tilt angle θ and of the insertion depth *h* able to avoid wedging are assessed against variations of hole's diameter *D* or clearance *j*.

4. SAMPLE CASE

Parallel kinematics machines are often characterised by potentially high performances but their actual behaviour is limited by difficulties in design and control, especially in the case of 6 axes robots, mainly due to their complex kinematics. A possible solution lies in the use of (several) simpler machines, characterised by limited mobility: hybrid machines may be designed (*e.g.*, a conventional "serial" wrist on top of a "parallel" shoulder) or mini-maxi architectures can be experimented; alternatively, a full-mobility task may be decomposed into elemental sub-tasks, to be performed by separate minor mobility machines, like done already in conventional machining operations and recently proposed also for PKM's [8]. In this case a proper mechatronic design allows to exploit, at least partially, the advantages of both architectures, while the disadvantages can be minimised. In this way it is possible to realise hybrid cooperative systems with many degrees of freedom, leading to a modular and reconfigurable system architecture.

The example here described is taken from the results of a research developed at the Department of Mechanics of the Polytechnic University of Marche, aimed at assessing the feasibility of complex assembly tasks (*e.g.* 6 axes operations) by means of the use of two cooperating parallel robots, both characterized by a simple mechanical and control architecture. Both machines are based on the 3-CPU architecture, meaning that the mobile platform is connected to the ground frame by means of 3 identical limbs, each one composed by the following joint sequence: Cylindrical, Prismatic, Universal. In the first case, however, Fig. 6a, joints axes are set in space so that the mobile platform can freely translate (without rotating) inside its 3D workspace, while in the second case, Fig. 6b, with a different setting of the joints, 3 degrees of freedom of pure rotation are obtained at the terminal (*i.e.* the mechanism is a spherical wrist).

Fig. 7 shows the functional architecture of the whole system: it has been first studied and designed by means of the simulation environment previously explained and now the physical prototypes are under construction. The control systems of the two machines are equipped with an impedance controller, so that the relative stiffness of the system can be varied during parts' mating to allow an effective accomplishment of the task but, on the other hand, the complexity of the hybrid position/force algorithms (needing proper force sensors and the availability of real time robots' inverse dynamics models) is avoided.

The simulations have shown the benefits of the prospected mechatronic architecture and allowed to tune the design of the mechanical and control systems. The translational robot, see Fig. 8a, is actuated by brushless

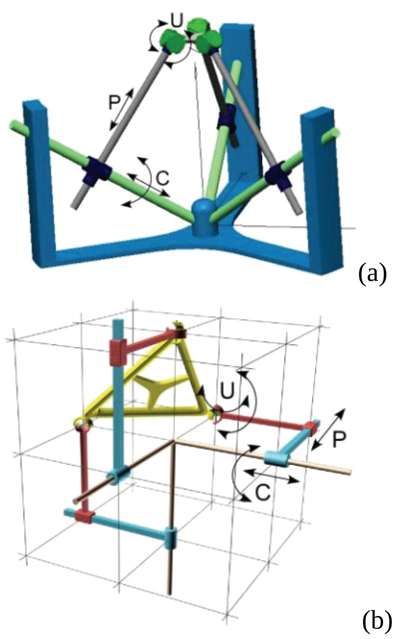

Fig. 6. Different concepts deriving from the 3-CPU mechanism: a) pure translations robot; b) spherical wrist.

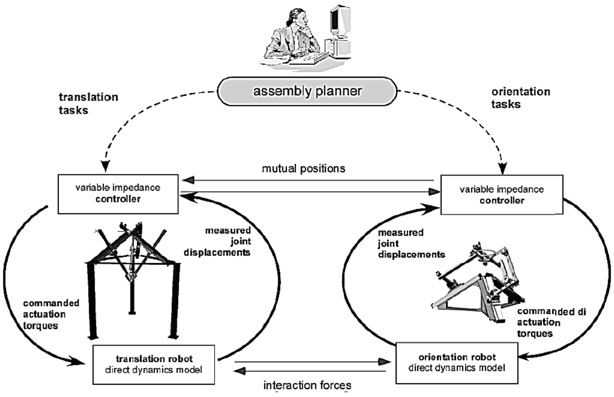

Fig. 7. Architecture of the assembly system based on cooperating parallel robots.

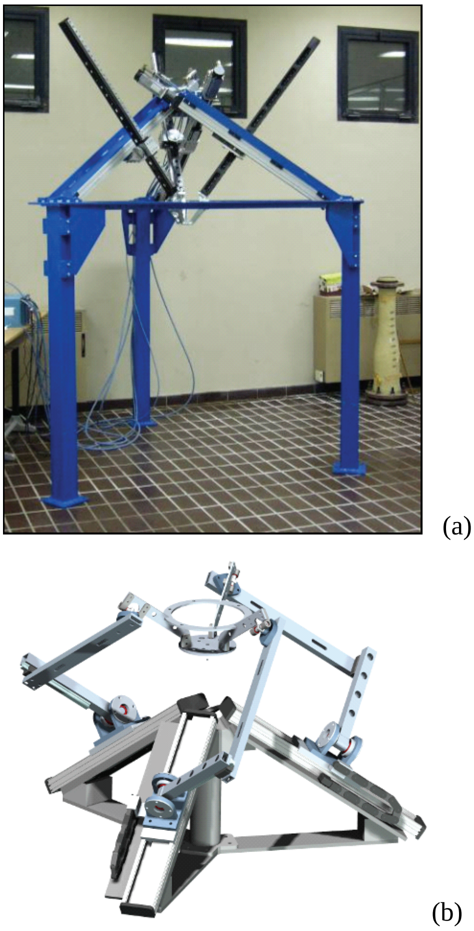

Fig. 8. Prototype of translation robot (a) and final design of spherical wrist (b).

motors and linear modules based on ball-screw drives; the controller is based on the DSpace DS1103 card and the code has been written in Matlab, tested in the mentioned virtual prototyping environment and then downloaded to the controller by means of the Matlab Realtime Workshop toolbox. The spherical wrist, instead, is presently under construction and Fig. 8b shows the final design: it will be directly driven by 3 linear motors by Phase and controlled by a Nation Instrument system based on the PXI/FlexMotion hardware.

5. CONCLUSIONS

The paper has presented the layout of a virtual prototyping environment developed at the Polytechnic University of Marche for the mechatronic design of advanced robotic systems. As an example, the architecture of a cell for mechanical assembly is presented: it is based on the functional splitting of complex tasks between two cooperating parallel kinematics machines with limited mobility and equipped by proper interaction control. The design phase has been completed already and the first experimentations are presently under execution.

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