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Mechatronic design of a parallel robot for high-speed, impedance-controlled manipulation

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***Abstract*-- The paper deals with the integration of mechanical and control aspects involved in the design of an innovative 3-dof parallel kinematics machine. Its mechanical architecture is based on the 3-PUU scheme, actuated by crank-rod mechanisms and direct-drive brushless motors. The robot architecture is conceived in order to obtain high flexibility and reconfigurability in performing impedance-controlled manipulation tasks. The (direct and inverse) kinematic and dynamic models are discussed, with special reference to their application in the control system. The application of the integrated mechatronic approach and its advantages are described. A full-scale prototype has been built; its hardware and software layouts are presented. The test phase is at present in progress; the preliminary results are satisfying.**

***Index terms*-- mechatronics, parallel kinematics machine, impedance control**

I. INTRODUCTION

One of the key-issues in the development of modern robotic systems is the mechatronic approach, i.e. the strict integration, since the earliest design phases, of mechanical, control, electrical and electronic aspects. Nevertheless, the industrial robot manufacturers rarely use this methodology, which could remarkably improve the overall performance of their products. On the contrary, they invest most of the resources to develop user-friendly man-machine interfaces, applied to tested mechanical architectures; the axes are usually separately controlled, once the trajectory is planned, by standard linear PID loops.

In most industrial cases, the robot design process is divided into two sequential phases: the mechanical design and the control system design; usually, the mechanical design is not influenced by the control system conception: the designer simply tries to obtain high structural stiffness, because a very stiff machine is easily controllable by means of decoupled linear loops applied separately to each axis.

On the other hand, if the mechanical architecture is conceived in parallel with a more sophisticated, model-based control strategy, it is possible to study exhaustively the behaviour of the overall system, emphasizing the peculiar properties of the mechanical architecture itself.

The traditional industrial approach of robot manufacturers and the alternative integrated mechatronic approach are compared in Fig. 1.

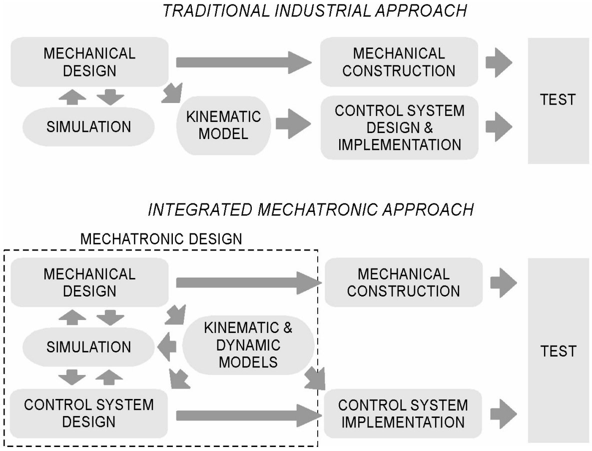

Fig. 1. Comparison between the traditional approach of robot manufacturers and the integrated mechatronic approach.

In the first case, the mechanical architecture is designed first of all, using the multibody simulation on the basis of the desired dynamic performance (i.e. the required motion) of the machine; the detailed design of each member is checked by means of FEM analysis considering the required robot motion and applied forces. Secondly, the control system is realized using the kinematic equations, regulating separately the position of each actuator in order to impose the desired end-effector position.

With the mechatronic approach mechanics and control are studied simultaneously; to this aim, not only the kinematic model, but also the dynamic model is obtained; the static model can be derived from the dynamic model, eliminating the inertial terms, or from the velocity analysis, applying the virtual works principle. The performance of the system is improved by means of proper compensation of the inertial and gravity terms; moreover, the static model allows to regulate, whenever necessary, the interactions with the environment.

The advantages of this approach are particularly evident for parallel robots [1]: as a matter of fact, their high dynamic performances, due to the limited moving masses, can be emphasized by means of the inertial compensation; this compensation is more important for PKM than for serial

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robots because the ratio between payload and machine moving mass is higher, and therefore the payload variations influence remarkably the machine behaviour.

Moreover, the high structural stiffness of a closed-loop kinematic chain allows to exert strong forces on the environment, and a model-based control system is necessary to exploit this feature.

For all of these reasons, one of the most important purposes of the Italian PRIDE research programme *(Parallel Robots Interacting with Dynamic Environment)* [2], funded by the Italian Ministry of Education, University and Research, is to design high-performance PKM, specifically conceived for tasks in which the contact with the environment is fundamental, by exploiting the mechatronic, model-based approach.

In particular, the paper deals with an innovative (patented) three-degree-of-freedom parallel kinematics machine [3], [4]. The direct and inverse kinematic and dynamic equations, necessary to realize the model-based control algorithm, have been obtained and are briefly discussed; these models have been used in all the project phases (simultaneous functional design of mechanics and control, detailed design, control algorithm implementation).

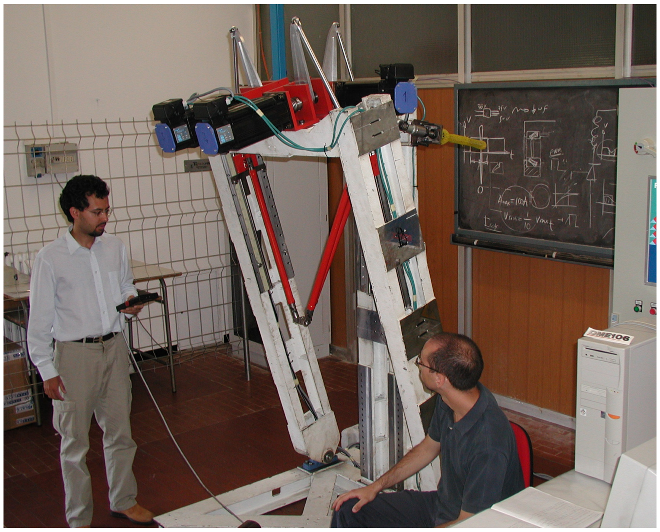

Fig. 2. The PRIDE prototype.

II. THE PROPOSED IMPEDANCE-CONTROLLED PARALLEL KINEMATICS MACHINE

The proposed PKM is shown in Fig. 2; its lightweight mechanical structure is based on the 3-PUU scheme, and the actuation of the three translating slider is obtained by means of rotating torque motors and crank-rod mechanisms (Fig. 3).

This robot has been conceived in order to obtain high flexibility and reconfigurability in performing impedance-controlled manipulation tasks. Force control algorithms like *HPFC* and *indirect force control* (*impedance control)* ([5], [6]) allow to widen the range of possible tasks; some applications, e.g. assembly, can be performed with reduced operational time [7].

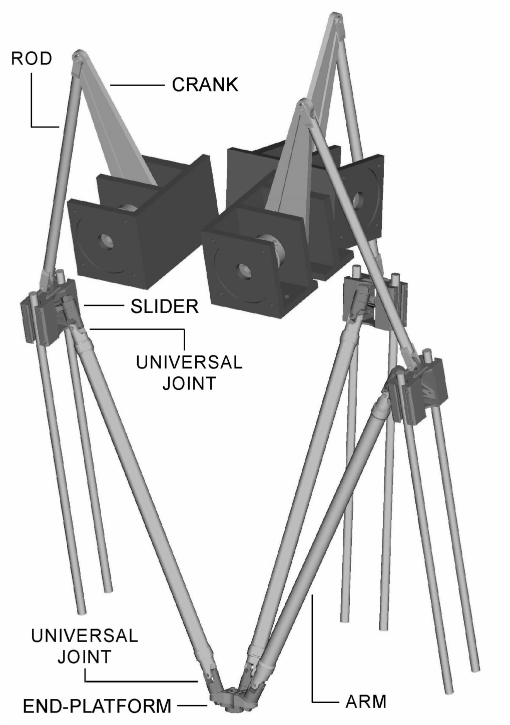

Fig. 3. 3-PUU architecture with crank-rod actuation.

Since the proposed solution avoids the presence of gearboxes and the components are low-friction the whole robot is mechanically reversible; this is one of the requirements for suitably applying impedance control, regulating the force exerted on the environment through the motor moments [8]. The impedance algorithm is expressed by the following equation:

$$\begin{aligned}\boldsymbol{\tau} = \mathbf{J}^T\left(\boldsymbol{\theta}\right)\left[\mathbf{K}\left(\mathbf{x}_d - \mathbf{x}\left(\boldsymbol{\theta}\right)\right) + \mathbf{D}\left(\dot{\mathbf{x}}_d - \dot{\mathbf{x}}\left(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}\right)\right)\right] + \\ + \boldsymbol{\tau}_g\left(\boldsymbol{\theta}\right) + \boldsymbol{\tau}_{in}\left(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}\right)\end{aligned} \tag{1}$$

where: $\boldsymbol{\theta}$ is the vector of the internal coordinates (motor angles); $\mathbf{x}$ is the vector of the external coordinates (end-effector position); the subscript d refers to the reference trajectory; $\mathbf{J}\left(\boldsymbol{\theta}\right)$ is the Jacobian matrix; $\mathbf{K}$ and $\mathbf{D}$ are the stiffness and damping matrices; $\boldsymbol{\tau}_g\left(\boldsymbol{\theta}\right)$ and $\boldsymbol{\tau}_{in}\left(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}\right)$ are the gravity and inertial compensation vectors.

Both the kinematic and dynamic models are necessary to realize the compensation of the gravity and inertial terms.

If friction is negligible, it is possible to regulate the force applied by the end-effector planning properly the reference trajectory and the stiffness and damping matrices: the robot end-effector behaves like a three-dimensional spring-damper system with stiffness and damping defined independently for each direction. Let us consider the robot motionless, exerting force on the environment; if the stiffness in a direction is low, the corresponding force component, is determined by the product of the corresponding stiffness matrix element and external coordinate error [8]. Theoretically, this is true for any stiffness, but if the stiffness is high the robot accuracy influences too much the force control accuracy.

When the end-effector must exert force in some directions, the corresponding values of the elements of $\mathbf{K}$ and $\mathbf{D}$ are lowered; on the other hand, during high-speed non-operative movements the actual trajectory must be very close to the reference trajectory, then the values of all the elements of $\mathbf{K}$ and $\mathbf{D}$ must be sufficiently high.

By impedance control it is possible to regulate the external interactions without force sensors; therefore the robot aptitude in performing complex and critical tasks increases, avoiding the drawbacks related to the placement of additional sensors on the end-effector (cost, mechanical complexity, loss of reliability, higher inertia).

III. MECHANICAL MODEL

The kinematic model of the PKM is obtained imposing for each arm the distance between the two universal joints. This leads to three constraint equations ($v_i = 0$, i=1..3) in six unknowns (the internal and external coordinates). On the basis of these three equations it is possible to develop the direct and inverse kinematic laws. The inverse position analysis is easy, because each constraint equation depends only on one internal coordinate (the motor angle corresponding to the considered leg), while the direct position problem is more complex, because each constraint equation contains all the external coordinates.

As regards the dynamic model, due to the complex direct kinematics, the simplest approach is to develop the Lagrange equations with multipliers, using six generalised coordinates (both the internal and the external robot coordinates) and the three constraint equations (closure of the three kinematic chains):

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = Q_j + \sum_{i=1}^{k} \lambda_i A_{ij} \qquad (j = 1..6) \tag{2}$$

where: $\mathbf{q} = \begin{bmatrix} x & y & z & \theta_1 & \theta_2 & \theta_3 \end{bmatrix}^T$ is the vector of the generalized coordinates; $L = T - V$ is the Lagrange function (kinetic energy-potential energy); $A_{ij} = \dfrac{\partial v_i}{\partial q_j}$ $(i = 1..3)$ are the partial derivatives of the constraint equations; λ_i are the Lagrange multipliers; $\mathbf{Q} = \begin{bmatrix} F_x & F_y & F_z & \tau_1 & \tau_2 & \tau_3 \end{bmatrix}^T$ is the vector of the generalized external forces, i.e. the forces exerted on the end-platform by the environment and the motor moments; friction is neglected.

The Lagrange multipliers λ_i can be obtained by means of the first three equations of system (2), related to the external coordinates; once the Lagrange multipliers are known, the remaining equations of system (2) provide the explicit formulas for the actuator moments.

The dynamic model of the robot can be used to obtain exact or simplified expressions for the terms $\boldsymbol{\tau}_g$ and $\boldsymbol{\tau}_{in}$ of the control law (1). The three components of $\boldsymbol{\tau}_g$ can be assessed imposing static conditions $(L = -V)$ and no external force $(F_x = F_y = F_z = 0)$ in (2). As regards the inertial compensation terms, they are obtainable subtracting the components of $\boldsymbol{\tau}_g$ to the results of system (2) solved in case of no external force.

IV. IMPLEMENTATION OF THE CONTROL ALGORITHM

The impedance algorithm requires at least the real-time computation of the Jacobian matrix, of the direct kinematic equations and of the gravity compensation terms; moreover, if high dynamic performance is required, it is necessary to add the compensation of the inertial terms (exact or simplified). Let us notice that the inertial compensation is useful moreover during high-speed non-operative end-effector movements, and can be avoided during the operative phases when the robot is in contact with the external environment or moves at low speed.

This heavy computational burden can be faced nowadays using the control units of the last generation, but represented an insurmountable obstacle only few years ago, and this was one of the causes of the PKM limited diffusion.

However, it is necessary to design properly the software implementation of the equations, in order to increase the control sampling frequency; to this aim, using symbolic mathematical packages, the kinematic, static and dynamic equations have been rewritten singling out the common terms, depending on the robot position, which can be computed only once per sampling time.

The outputs of impedance control are the reference moments that are imposed by three separated current loops, performed by the motor drivers, considering the torque constant K_t (Fig. 4) [9].

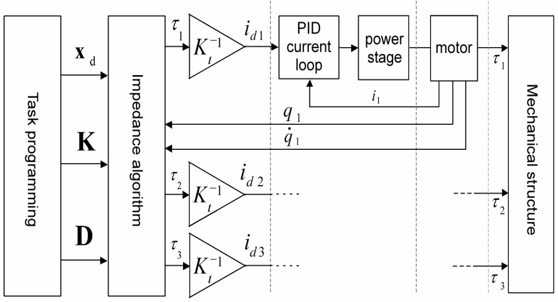

Fig. 4. Control system layout.

The hardware layout of the prototype control system is essentially constituted by a Robox RBXM modular unit and three digital drivers Phase Motion Control AxV. The main control unit is characterized by an AMD AM5X86 CPU with 4 Mb of DRAM, resident operative system and diagnostic software. The RBXM is programmed via serial port RS232 by a standard external PC through the software shell RDE, and the operative programs and parameters are supported by a 2 Mb flash card.

The software shell RDE is an interactive programming environment. It allows to write, debug and compile off-line the code that implements the control algorithm and the task program. This code is subsequently uploaded into the RBXM unit. The code related to control algorithm and kinematic equations is written in C++ language, extended with specific, real-time Taskbin++ classes. On the contrary, the task program (i.e. the description of the machine movements and of the necessary control parameters) is written in RHLL language, developed for robotic and automation applications. This language is characterized by procedural and parametric instructions that define the displacements and the speeds in different coordinate sets, the delays and the geometrical interpolations.

Another function of the RDE shell is the on-line monitoring of the control unit state (registers values, reference and actual positions of the axes); this function is useful in the debugging phase of the task programs.

The parameters of the digital drivers are programmed off-line by the same PC where the RDE shell is installed, using the software package AxV Cockpit; therefore, the robot is entirely programmable by a standard personal computer. When no program is running, the robot can be moved manually by a telecontrol at reduced speed to easily plan the task.

With the actual software configuration, the digital drivers AxV can receive from the main control unit a reference speed (when the robot is position-controlled) or a reference current (when the robot is impedance-controlled). However, when the compensation of the moments due to the gravity and inertial terms is performed by the main control unit, the reference to the drivers is necessarily a current proportional to the torque.

Without gravity compensation, the weight of all the mobile members increases the vertical force applied by the end-effector due to the mechanical architecture; then, when the impedance algorithm is used to regulate the exerted force, the gravity compensation must be active. In this case, the references for the currents are computed with a sampling frequency of 200 Hz, while the current loop is performed at 16 kHz.

During high-speed non-operative movements the stiffness and damping values are high and the actual trajectory is generally very close to the reference trajectory; in this condition the inertial compensation can be based on the reference trajectory and computed off-line, without lowering the sampling frequency.

V. EXPERIMENTAL TEST

The first tests on the prototype seem to encourage the direction of the research: the model-based control algorithms emphasize the peculiar characteristics of the parallel architecture and, in particular, the good dynamic performance due to the limited moving masses, with a well predictable machine behaviour. The robot is capable of exerting a force of 300 N in the vertical direction, and the reachable acceleration is about 4g [10].

As regards the accuracy in the control of the exerted force, in Fig. 5 there is a comparison between the force imposed by the control system and the measured force, in case of a desired vertical force of 300 N exerted on a steel plate; the contact occurs between 0.7 s and 2.6 s. The measured force is lower (about 7%) due to the presence of friction in the robot joints, which is not compensated for by the control algorithm. The experimental results are satisfactory, but if high accuracy is required (better than 3%) friction must be properly taken into account and compensated for.

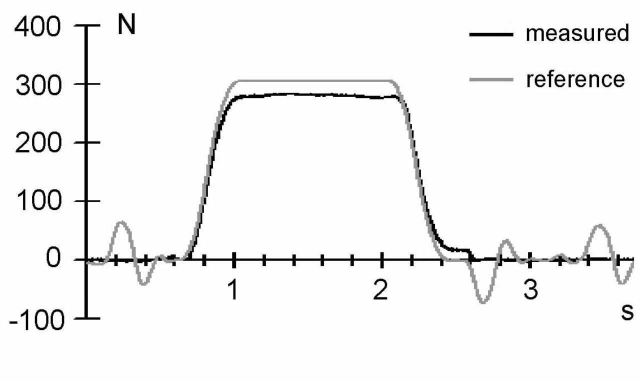

Fig. 5. Vertical force exerted by the end-effector.

VI. CONCLUSION

Nowadays parallel kinematics machines still represent a small percentage of the industrial robots, and their cost is generally high in comparison with traditional serial robots because of the sophisticated mechanical solutions [11]. The diffusion of PKM would greatly increase if their cost were lower enough to be competitive respect to serial arms. This is possible, because the links of the parallel robots are simple and modular; the most expensive parts are the high-precision joints. The PRIDE prototype has been realized using (whenever possible) off-the-shelf mechanical components; its performance is not only due to the quality of the components, but to the concurrent, synergic design of mechanics and control. Therefore, it demonstrates the possibility of realising low-cost, high-speed parallel robots for manipulation, capable of fulfilling the requirements of a wide range of industrial applications. Moreover, the research underlines the benefits of the integrated mechatronic approach for advanced robotic applications.

VII. ACKNOWLEDGEMENT

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