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IMPEDANCE APPROACH FOR CONCEPTUAL DESIGN OF MECHATRONIC SYSTEMS

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Abstract: *Conceptual design approach for mechatronic systems (MS) with dynamic interaction with technological environment (TE) has been presented in this paper. It is based on the exploitation of impedance control method with its 3 known approaches to perform the reference task function. By analyzing the dynamic interaction of MS with TE ideas and design approach are generated to design either some subsystems– drive, mechanic, sensor, control and information or the whole MS. This allows the desired quality parameters and functionality to be achieved. Applying this approach some MS have been designed, such as positioning robot for feeding operations, MS for monomolecular films deposition, Robot for micro & nano manipulations, etc. Experimental results obtained from those typical examples illustrate the effectiveness of the proposed conceptual design approach for MS dynamically interacting with TE.*

Key words: *impedance approach, conceptual design, mechatronic system, dynamic interaction*

1. INTRODUCTION

Application of mechatronic and robot systems into new technologies fields such as control measuring operations, deburing and assembly operations, surgical assisted operations, genetic and cell manipulations in biology and medicine etc. put new requirements to provide new functional and qualitative characteristics. Mainly they are high kinematic and dynamic accuracy, wide range of output link velocity while the unevenness is guaranteed, high sensitivity for micro and nano motion realization, etc. Most of the cases mechatronic systems (MS) are performing contact tasks or they are characterized with dynamic interaction with the technological environment (TE). In the case of telemanipulation control the interaction between the MS and the operator has to guarantee successful performance of the teleoperation task in a minute operation. The design process generally consists of iterative procedures between reference task function analysis, conceptual design, embodiment design and details design. In this paper the first two stages of the design process for MS functionally interacting with the TE are considered. Here, the impedance control approach is used as a means to accommodate or to control the dynamic behaviour of MS while it is interacting with the TE in order to improve the quality of the technological process or to improve the system functionality. In impedance control the contact force is regulated by controlling the position and its relationship with the force, i.e. mechanical impedance. For most of technological processes MS end-effectors are not obligatory to be in contact while they perform the reference tasks. In this paper the case study is MS functionally dynamic interacting with their TE.

The impedance control is realized by three approaches [1]. A lot of works developed the first approach for impedance control by impedance controller use one of the known eight approaches [2]: constant PD control, model based computed torque control, adaptive control, robust saturation-based control, model based computed torque control, sliding mode-based impedance control [3], learning impedance control [4] or quaternion-based impedance controller [5]. They are characterized with the different shortcomings such as: the desired impedance cannot be maintained because of changes in the robot configuration and velocity; model-based computed torque control is too sensitive too uncertainties in the dynamic model of the robot; the measurement noise decreases the accuracy of the estimation of the dynamic parameters; requirement of extensive computation and high gains etc.

The second approach for impedance control, i.e. by redundancy of joints, is reduced for one joint into the third approach for impedance control realized by redundancy of drives for each robot joint. Many researchers developed the third approach for impedance control used antagonistically driven robot joints by two actuators via tendons [6, 7]. Antagonistic stiffness, for which the modeling procedure for a completely general kinematic system along with a stiffness formulation technique was developed [8], seems to be very unique and promising to design a control of future robot manipulators and mechatronic peripheral devices with high precision requirements under various operational impacts and disturbances. The shortcomings here are consisted of redundancy of drives, complicated servo mechanisms, increased energy consumption etc.

All these shortcomings of the known approaches for impedance control realization specify the specter of practical applications defining in this way the approach for their design. By analyzing the dynamic interaction of MS with TE ideas and design approach are generated for some subsystems– drive, mechanic, sensor, control and information as well as the whole mechatronic system. This could allow the desired quality parameters and functionality to be achieved.

The aim of this paper is to develop an approach for conceptual design of MS, where through analyzing the dynamic interaction of MS with TE, ideas are generating and design impedance control approach could be applied as for the separate MS subsystems - drive, mechanical, sensor, control, information and data acquisition, and for the MS as whole, in order to achieve the desired system parameters or new functional features.

2. IMPEDANCE APPROACH FOR CONCEPTUAL DESIGN OF MS

To achieve the desirable accuracy and functionality of the MS is the main goal of the design engineer. It is emphasised that the system design implies not only an intuitive act of simple creation, but also the use of obtained results by means of analysis, optimisation, and interpretation except the individual experience. The high strategies that are involved in the achievement of a CAD system improve the design process and ensure a higher quality of the end product - MS interacting with the remain TE. The consecution of design process for development of such MS based on the impedance control approach is shown in the Fig. 1.

2.1. Task formulation (branch oriented task modeling).

The task formulation is one of the most important stages of the development of a certain system. The reference task function, which has to be achieved by the micromanipulation systems to be designed, is considered in dimensional, energetic and working spaces. Since the subject of this paper is mechatronic systems dynamically interacting with the technological environment the appropriate control approach has to be chosen. As it was mentioned here the impedance control is used for that purpose. The mechanical impedance consists of two components - knot and non-knot components. The knot mechanical impedance Z_0 is determined by the stiffness *K* and damping *B*. The non-knot component Z_1 reflects the inertia properties of the mechanical system.

So, the definition of the dynamic interaction is to determine the targeted actuator knot or not-knot mechanical impedance expressed by a given external impact T_i acting on mechatronic system end-effector and the desired reaction on the system (reference parameters of motion), where φ_a φ_r are actual and reference parameters:

$$\Delta\varphi = \varphi_r - \varphi_a(T_i)\,,$$
$$\Delta\dot{\varphi} = \dot{\varphi}_r - \dot{\varphi}_a(T_i)\,, \qquad (1)$$
$$K(\varphi_r - \varphi_a) + B(\dot{\varphi}_r - \dot{\varphi}_a) = T_i\,.$$

2.2. Dynamic interaction definition.

Torque of interaction T_i between the mechatronic system output link and technological equipment can be expressed by the equation, where $\boldsymbol{T}(\varphi,\dot{\varphi})$ is knot component of the MS impedance:

$$T_i = T(\varphi,\dot{\varphi}) - J\frac{d\dot{\varphi}}{dt} = K(\varphi_r - \varphi_a) + B(\dot{\varphi}_r - \dot{\varphi}_a) - J\frac{d\dot{\varphi}}{dt}\,. \qquad (2)$$

The dynamics of the end-effector of the technological equipment, when it is on ideal rigid body, is expressed by the equation, where J_Σ is inertia tensor of the TE end-effector; T_e - unknown torques and impacts:

$$J_\Sigma \frac{d\dot{\varphi}}{dt} = T_e + T_i \qquad (3)$$

The motion equation of the system "mechatronic system actuator joint shaft - technological equipment" is:

$$T_i = T(\varphi,\dot{\varphi}) - J\frac{d\dot{\varphi}}{dt} = K(\varphi_r - \varphi_a) + B(\dot{\varphi}_r - \dot{\varphi}_a) - J\frac{d\dot{\varphi}}{dt}\,. \qquad (4)$$

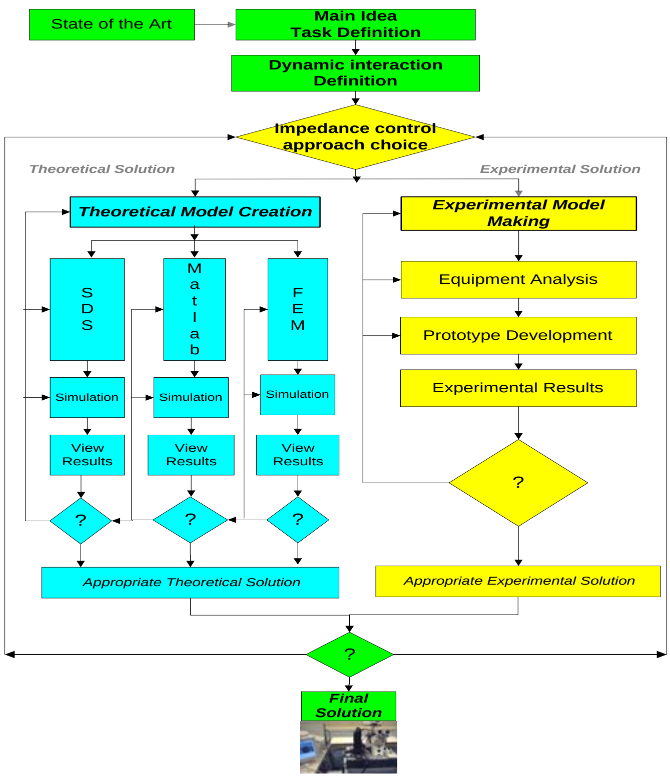

Fig.1. Design Process Algorithm for MS dynamic interacting with TE.

For the feeding operation is most important to assure smooth motion, i.e.: $d\dot{\varphi}/dt \approx 0$. The equation (2) will be:

$$(J_\Sigma + J)\frac{d\dot{\varphi}}{dt} = K(\varphi_r - \varphi_a) + B(\dot{\varphi}_r - \dot{\varphi}_a) + T_e - J\frac{d\dot{\varphi}}{dt}. \quad (5)$$

The equation (5) means that by variation of the actuator knot mechanical impedance Z_0 to reject the disturbances at some impacts. The desired actuator shaft response $\varphi_a(t)$ and $\dot{\varphi}_r$ to the reference motion φ_r and $\dot{\varphi}_r$ and the external torques T_i is defined by (1).

2.3. Choice of the Impedance control approach.

To control the mechanical impedance is necessary to set up two control sets [1]:

$$\{S_f\} = V_0(t), \quad (6)$$

$$\{S_Z\} : Z_0(F_{\mathbf{int}}, Q). \quad (7)$$

The first one S_f is the flow source. It defines the requirements to the output link motion. The second control set $\{S_z\}$ express the mechanical impedance of the actuator *Z*. It defines the desired dynamic parameters of the MS actuators.The possibilities to set these two control sets for any MS joint define which one of the 3 impedance control approaches will be used further for the MS design.

2.3.1. 1st *Approach* - by Impedance Controller using Feedback.

Control strategy applying for MS design using the first approach of impedance control is based on the accommodation impedance control scheme for adjusting the targeted MS mechanical impedance expressed by an expected external impact acting on MS end-effector and the desired dynamic reaction on the system [9]. This scheme consists into 2 parts (Fig. 2). First one is a feed forward controller, constructed off-line using the obtained dynamic model [10]. The open-loop impedance control involves off-line planning of the targeted actuator mechanical impedance for the desired output link velocity $\dot{\varphi}_r(t)$, smoothness of motion $\Delta\dot{\varphi}(t)$ and expected impacts and disturbances T_i, determining the actuator control sets $\{S_f\}$ and $\{S_z\}$. This allows open loop disturbances and impacts rejection. The second part is a feedback controller used to compensate on-line small perturbation of the expected impacts and non modelled dynamics.

2.3.2. 2nd *Approach* - by Redundancy of MS joints

The second approach for impedance control is realized by redundancy of joints. To apply this approach first is necessary to determine the number of redundant joints for the reference set of manipulating tasks. The second one is how to distribute the control of joints in regarding of the kinematic [11] and dynamic sensibility [12] and the task complexity to be performed [13, 14]. Let's consider how can be realise reference task function for deburring by the second approach for impedance control in a simple case of a plane trajectory motion with desired dynamic interaction in one direction only. For that case a robot with minimum one DOF more than the task function is necessary. Planar structure *R⊥T⊥T* is taken here as an example [15].

Each degree of freedom can be taken as redundant one in arbitrary case. The sensibility analysis shows the following results for corresponding sensibility coefficients λ_i, (i = 1,..,3) and directions $X^{(i)}$, (i = 1,..,3), where h_1, p_3 are geometrical parameters.

$$\lambda_1 = 1,$$

$$\lambda_2 = 0,$$

$$\lambda_3 = 1 + q_2^2 + (h_1 + p_3 + q_3)^2,$$

$$X^{(1)} = \begin{bmatrix} 0 & \frac{q_2}{h_1 + p_3 + q_3} & 1 \end{bmatrix}^T,$$

$$X^{(2)} = \begin{bmatrix} \frac{1}{q_2} & -\frac{h_1 + p_3 + q_3}{q_2} & 1 \end{bmatrix}^T, \quad (8)$$

$$X^{(3)} = \begin{bmatrix} -\frac{(h_1 + p_3 + q_3)^2 + q_2^2}{q_2} & -\frac{h_1 + p_3 + q_3}{q_2} & 1 \end{bmatrix}^T$$

The second coefficient that is zero assures non sensibility on the direction collinear to $X^{(2)}$ during the end-effector motion. On the remaining two orthogonal directions the sensibility is fixed or variable respectively and following the third one the sensibility depends on the robot configuration. It can be realized separately by one generalised coordinate or by both of them simultaneously.

For example the robot deburring task is considered. The end-effector moves on the surface to be deburred. Hence, the non-sensibility direction coincides with the surface normal vector. For the remaining directions the robot has some sensibility according to the executing trajectory. In our example the reference deburring trajectories having these characteristics are arbitrary. If that additional requirement appears, the problem of obtaining the desired sensibility arises which could be solved using structures with redundancy DOF. The sensibility ellipsoid is visualised (Fig. 3.) for the considered structure in a limited region of variation of the generalised coordinates.

2.3.3. 3rd *Approach* - by Redundancy of Drives for desired MS joint

The actuators with drive redundancy are a simplified model of the antagonistic drive in the living nature. Actuation and kinematic redundancy are the means by which living species control the dynamic response and modulate their end-effector stiffness.

The synthesis of actuators with drive redundancy is based on the motion transition method [17]. It consists of two-zone dynamic controlled gearing on the actuator output link through the introduction of an antagonistic drive unit that is identical to the existing one. This method also allows eliminating or reducing the influence of uncertainties on the kinematic chain of the mechatronic drive due to closed loop structures with the addi-

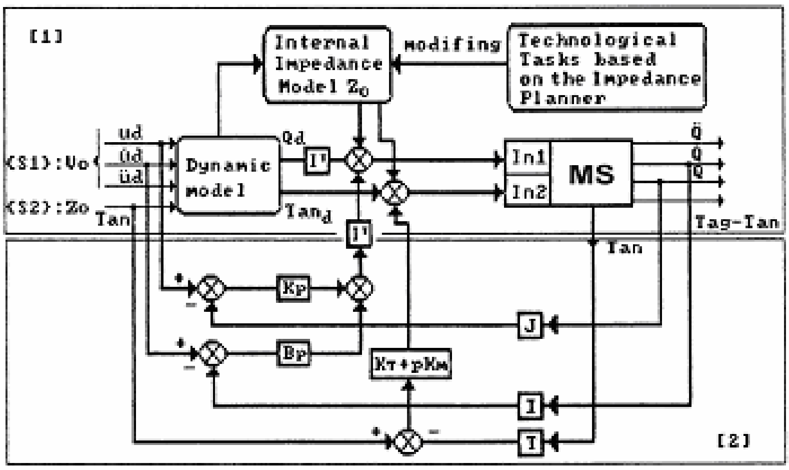

Fig. 2. General Accommodation Impedance Control Scheme ([1] - feedforward controller, [2] - feedback controller).

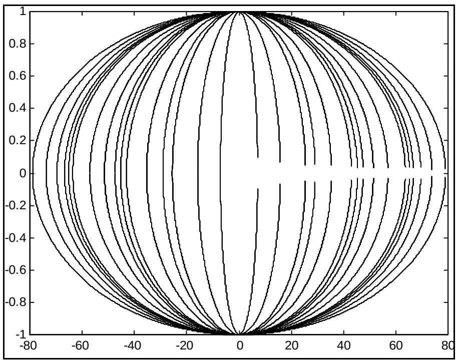

Fig. 3. Sensibility ellipsoid for the considered structure R⊥T⊥T.

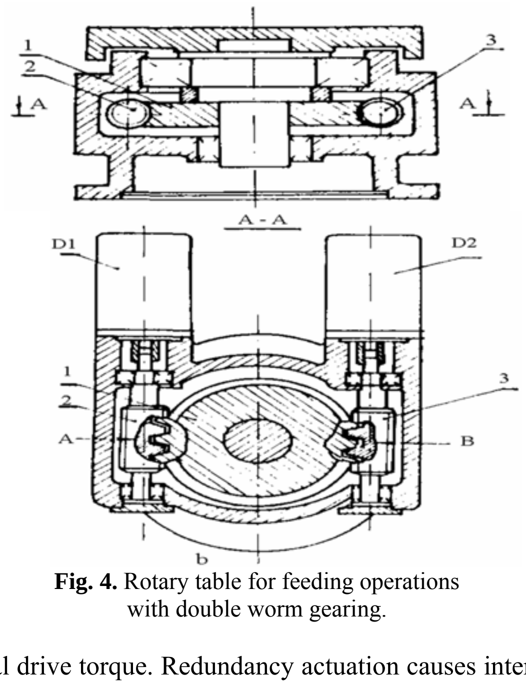

Fig. 4. Rotary table for feeding operations with double worm gearing.

tional drive torque. Redundancy actuation causes internal force/torque in the transfer mechanism. This torque does not perform any effective work to the external world. But the actuator joint stiffness and damping depend on this internal torque [18, 19].

In such way the knot mechanical impedance Z_0 (K, B) [1] can be controlled. E.g., the damping and the stiffness of a double worm gearing in the rotating table for feeding operations (Fig. 4) are:

$$B_w = B_c + \frac{2\mu . f_T(a)}{\dot{\varphi}_{OL} d_k}\left[1+\frac{\sin(\alpha_1-\rho_1-\rho_0)\cos\rho_2}{\sin(\alpha_3+\rho_1+\rho_2)\cos\rho_0}\right]T_a = B_c + B_a(T_a), \quad (9)$$

$$K = \frac{0,8184.10^6 n_0}{\cos\lambda}\sqrt{\frac{T_a}{m_0 y_k d_w W(\alpha)\cos\alpha}} . \quad (10)$$

So, controlling the internal torque T_a the knot mechanical impedance can be control according to (3 & 4) since the output link motion of the transfer mechanism can be performed at different levels of the motor activaon.

2.4. Multilayer Design Approach comprising both theoretical and experimental investigation

The cycles comprising both theoretical and experimental investigation, which a mechanical system has to go through after the task formulation and choice of the impedance control approach to be used for control of dynamic interaction and before it could be launched on the market, is shown in the upper side of the Fig. 5. The first step of the cycle is represented by the Predesign. The initial project is designed with a dedicated design program such as AutoCAD, ProEngineer, CADDS5, EUCLID, etc. One obtains the first basis for simulation and computation with solid bodies procedures.

The simulation model is obtained by means of interface data transfer. A good accuracy of model description may be directly obtained by using the own constructor & design modules of the simulation programs (such as ADAMS, SDS, etc.). The finite elements (FE) analysis is achieved on the partially improved SDS-model. Usual software tools, such as ANSYS, NASTRAN, etc. are involved. They compute deformations, eigen values, and distributions of strength and perform modal analysis of the studied system. The process will be normally repeated several times (S1, S2, S3) until an optimized solution is achieved. Several variants of (pre)projects (P1-P3) were developed from optimization stages on SDS or ANSYS. Additionally, results of simulation built a data set to improve the control. The synthesized regulators could be implemented in MATLAB/SIMULINK, or directly in SDS. The prototype, obtained as design after all these operations, has to be practically achieved and experimentally tested (for example with LMS/CADAX). In

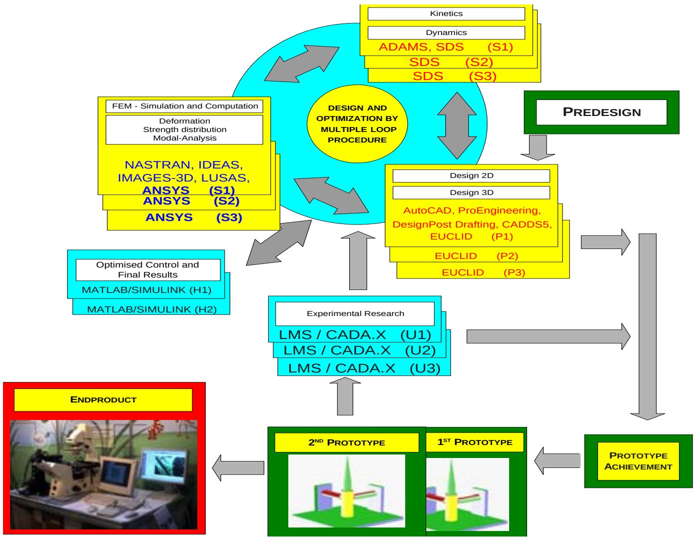

Fig. 5. Cycles of design and optimization with integrated strategies. Ways towards the optimized design and control.

case of unsatisfactory results, further optimization activities by multiple loop procedure should be resumed. The final solution is the MS with an optimized structure achieved by repeating the design and optimization cycle.

3. MS EXAMPLES BASED ON THE IMPEDANCE APPROACH FOR CONCEPTUAL DESIGN

The following typical examples of MS realized by developed impedance approach for conceptual design are:

Positioning robot for feeding operations with drive redundancy following the 3rd approach for impedance control [19, 20]. Here the reference task are characterized with the following main requirements:

- High dynamic accuracy regardless dynamic interaction between its output link and technological equipment;
- High resolution for micro rotation;
- Large ratio max-to-min velocity, especially low velocities without stick-sleep effects.

MS for monomolecular films deposition applying the 1st and 3rd approaches for impedance control [21, 22]. The reference task requirements to the barrier drive are: - Low compression speed due to the barrier below 1mm/s which are especially useful when fusion of domains starts and for smooth precise control of surface pressure. At the same time large velocities about 10 000 mm/s are required for cleaning the through and controlling the surface pressure when fast deposition on large substrata takes place. This is a speed ratio of 10 000. Smooth motion. i.e. motion with guaranteed desired unevenness to keep the surface layer; - High resolution for micro transition, e.g. 1 μm, for precise control of surface pressure. The surface pressure sensor, which main function is to measure and to feed back the surface pressure to the control system of a Langmuir trough during a monolayer film deposition process is designed using the control of the force of interaction between Wilhelmy plate and the liquid through electromagnetic coil current. In this way the sensor measures directly the force required to suspend a plate at a liquid surface. With the tare compensation a measuring range of ±100mN/m with resolution of 10 mN/m is achieved.

- *Robot for micro and nano manipulations* with hybrid approach for teleoperation control with impedance scaling applying the 1st approach for impedance control [23, 24]. The main problem here is that human operator has no perception about the robot end-effector dynamics and space size (micro or nano dimensions) in which it manipulates. Hence, in the case of cell micro and nano manipulations a MS has to provide the operator with the feeling that he knows the dynamics of the objects to be manipulated. This is realized by introducing a virtual mechanical impedance characterization, which is nonlinear scaling with corresponding constant. It is also called impedance scaling. In this way the teleoperation control can realize a proper physical coupling between the macro and nano world *appropriate* for the different operator perception.

- *Flywheel energy storage battery* applying 1st approach for impedance control [25]. The main problem here is to control the interaction between the TE and flywheel in order to accumulate or to generate the energy.

4. CONCLUSIONS

Conceptual design approach for MS with dynamic interaction with technological environment has been developed. It is based on the exploitation of impedance control method with its 3 known approaches to perform the reference task function. By analyzing the dynamic interaction of MS with TE ideas and design approach are generated to design either some subsystems– drive, mechanic, sensor, control and information or the whole MS. This allows the desired quality parameters and functionality to be achieved.

The obtained features of MS designed following this approach consist into:

- controlled modification of the MS impedance to control the dynamic interaction between MS and TE;
- micro motions of the barrier - particularly 0.001mm, at a range of motion (350 mm) and a big range of loading of the output link;
- smooth motion in a wide technological max-to-min velocity ratio (1:10000) regardless of the force interac-

tion at adjusting the actuator impedance with the technological equipment impedance;

- Effective manipulation in micro and nano space in a minute operation;

- Effective control of discharge and charge processes in flywheel storage battery while it dynamically interacts with the TE.

Experimental results obtained from typical examples of MS illustrate the effectiveness of the proposed conceptual design approach for MS dynamically interacting with TE.

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