Research and design of modular robotic manipulator for chemical aggressive environment

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***Abstract*— This paper deals with research and design of industrial robotic manipulator which is suitable for operation in aggressive environment (high pressure/temperature, acid or lye). The main field of application is a task of operation and manipulation in industrial degreasing and paint removing lines. For this purpose a special three DoF parallel spherical wrist was constructed. This allows a placement of all the vulnerable components of the robot such as drives and electronics outer the end-effector space, which may contain aggressive chemicals. All the positioning of the effector is performed by a system of mechanical transmissions which allow separating it from the rest of the machine by a waterproof barrier. Second part of the robot consists of three-arm serial manipulator with three DoF connected to moving support which results in final seven degrees of freedom kinematics. The paper deals with kinematical analysis of the manipulator and presents some basic approaches for motion planning and control.**

Keywords: robotics, industrial robotic manipulator, mechatronics, motion planning and control, parallel spherical wrist

I. Introduction

The problem of design of new robotic manipulator for aggressive environment operation (AGEBOT) is a part of research project in cooperation with industry which is in progress at our department. The goal was to develop a robotic arm suitable for manipulation tasks and operation of industrial degreasing and paint removing lines. Such machines are being used for cleaning, degreasing or conservation of metallic or non-metallic parts which have to be processed during manufacturing operations. The machine usually uses some sort of chemical like acid, lye or special degreasing lotion which is applied under high pressure and temperature on the surface of the cleaned components in order to remove all the remains of grease, cutting or tempering oil or mechanical dirt. It consists of several separated chambers which perform the operations of washing, rinsing and drying. Usual way to manipulate the cleaned parts between separate chambers is to use a human operator, conveyor belt or simple right-angled manipulator. Our goal was to improve the efficiency, reliability and the overall throughput of the whole system by introducing an advanced robotic manipulator which could replace the above stated mechanisms. Most of the commercially available robots are not suitable for this task, because of the aggressive environment, which could damage the sensitive parts of the robot (drives, electronics or wiring) or decrease their service life significantly. For this purpose a special three DoF parallel spherical wrist was constructed. This allows us to place all the vulnerable components outer the end-effector space, which has to be positioned in the cleaning chamber and exposed to aggressive chemicals. This structure allows safe separation of the wrist from the rest of the machine by a waterproof barrier. (Fig.1)

The paper deals with the construction of the robotic arm and presents the algorithms used for its control. Chapter two contains kinematical analysis of the system, chapter three describes an approach to motion planning and control and the last chapter presents the overall structure of the control system.

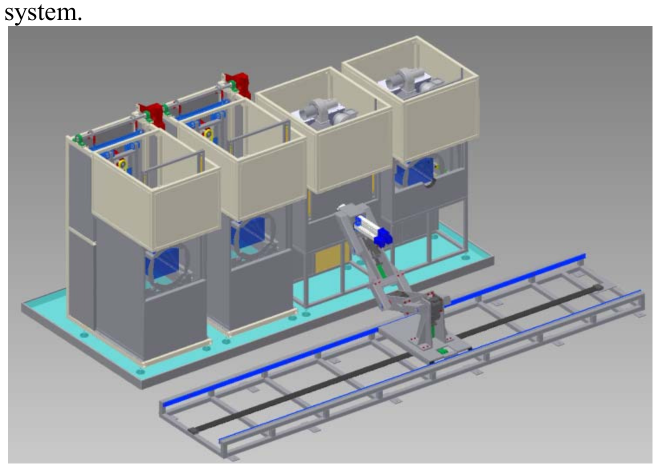

Figure 1. Degreasing line equipped with AGEBOT manipulator

II. Kinematical analysis

AGEBOT consists of two main parts (see Fig. 2) - *Serial manipulator (SM)* and *parallel manipulator (PM).*

SM is represented by the common serial manipulator with 3 DoF (2 translation DoF and 1 rotation DoF) and it is mounted on the linear belt support.

PM is represented by the parallel spherical wrist manipulator [1], with 3 rotation DoF which make possible positioning the AGEBOT's end-effector via the Euler angles (XYZ).

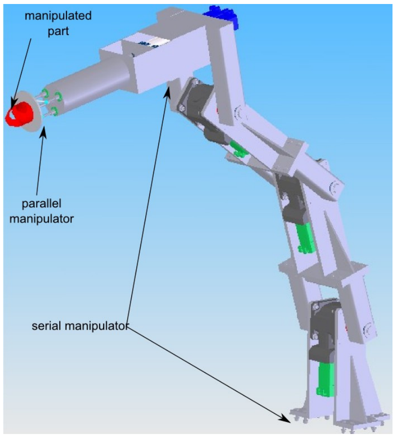

Figure 2. AGEBOT (SM + PM)

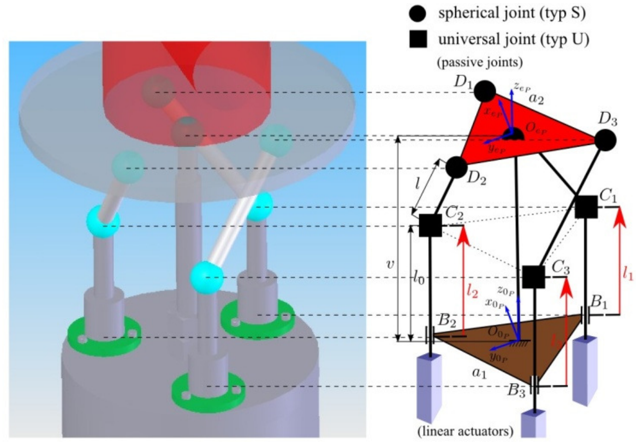

Figure 4. Parallel manipulator

We define the joint coordinates Θ and the generalized coordinates $\boldsymbol{X}$ of the AGEBOT:

$$\boldsymbol{\Theta} = \begin{bmatrix}\boldsymbol{\Theta}_S^T & \boldsymbol{\Theta}_P^T\end{bmatrix}^T, \; \boldsymbol{X} = \begin{bmatrix}\boldsymbol{X}_S^T & \boldsymbol{X}_P^T\end{bmatrix}^T \tag{1}$$

Where subscripts S and P denote the coordinates of the SM and PM respectively. Design parameters of the AGEBOT are supposed to be:

$$\boldsymbol{\xi} = \begin{bmatrix}L_1 & L_2 & L_3 & L_4 & L_5 & a_1 & a_2 & l & v & \psi\end{bmatrix}^T \tag{2}$$

Where L_i are lengths of the links of SM, a_i are lengths of the sides of the equilateral triangles representing the base and end-effector of the PM consequently, *l* is a length of the links connecting linear actuators to the end-effector, v is the height of the PM and ψ is a mutual torsional turning of the base and end-effector about z_{0P} axis for the PM's home position ($X_P^T = 0$). Figures 3 and 4 show CAD model and layout of SM and PM respectively.

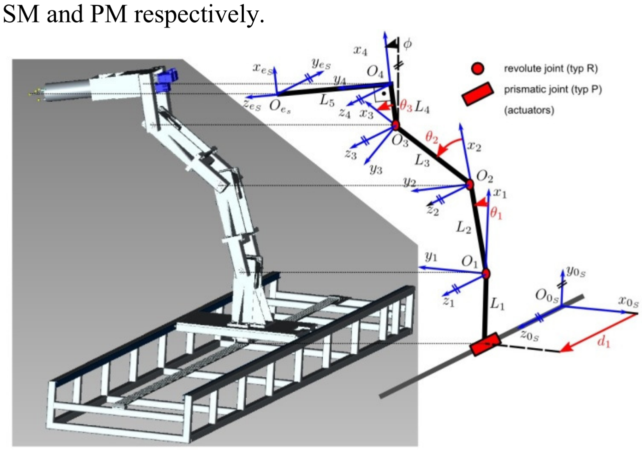

Figure 3. Serial manipulator

There are two main problems regarding kinematic description of the AGEBOT. The *forward kinematic problem* (determination of the generalized coordinates X for the given values of the joint coordinates Θ) and the *inverse kinematic problem* (determination of the joint coordinates Θ for the given values of the generalized coordinates X). In general case only the forward kinematic problem for serial manipulators can be solved analytically. The next chapters deal with these kinematic problems separately for the SM and PM of the AGEBOT. It is shown that there is no analytical solution for the forward kinematic problem of PM.

A. Forward kinematic problem for SM

The joint and generalized coordinates of the SM are, see Fig. 2 (upper subscript denotes coordinate system which the coordinates of the point is given in):

$$\boldsymbol{\Theta}_S = \begin{bmatrix}d_1 & \theta_1 & \theta_2 & \theta_3\end{bmatrix}^T, \boldsymbol{X}_S = \begin{bmatrix}\boldsymbol{O}_{e_S}^{0_S} \\ \phi\end{bmatrix} \tag{3}$$

Where $\boldsymbol{O}_{eS}^{0S}$ is the position vector of the end-effector of AGEBOT and ϕ is orientation angle of the terminal link of the SM.

The forward kinematic problem can be expressed through the homogenous transformation matrices [2]

$$\boldsymbol{T}_i^j = \begin{bmatrix} & \boldsymbol{R}_i^j & & \boldsymbol{p}_i^j \\ 0 & 0 & 0 & 1\end{bmatrix}$$

which describe the position (translation vector $\boldsymbol{p}_i^j$ and rotation matrix $\boldsymbol{R}_i^j$) of the frame $F_i = \boldsymbol{O_i} - \boldsymbol{x_i y_i z_i}$ with respect to the frame F_j. Notice that all frames are chosen according to so called Denavit-Hartenberg notation [3].

The following holds:

$$\boldsymbol{T}_{e_S}^{0^S} = \boldsymbol{T}_1^{0_S}(d_1) \cdot \prod_{i=2}^{4} \boldsymbol{T}_i^{i-1}(\theta_{i-1}) \cdot \boldsymbol{T}_{e_S}^4 \tag{4}$$

Where:

$$\boldsymbol{T}_1^{0_S}(d_1) = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & L_1 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{T}_i^{i-1}(\theta_{i-1}) = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & L_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i & 0 & L_i\sin\theta_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{pro} \quad i = 2\ldots 4$$

$$\boldsymbol{T}_{e_S}^4 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & L_5 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Generalized coordinates of the SM are directly given by the elements of $\boldsymbol{T}_{e_S}^{0_S}$.

$$\boldsymbol{X}_S = \begin{bmatrix} -L_5\cos\theta_{1,2,3} - L_4\sin\theta_{1,2,3} - L_3\sin\theta_{1,2} - L_2\sin\theta_1 \\ -L_5\sin\theta_{1,2,3} + L_4\cos\theta_{1,2,3} + L_3\cos\theta_{1,2} + L_2\cos\theta_1 + L_1 \\ d_1 \\ \theta_1+\theta_2+\theta_3 \end{bmatrix} \quad (5)$$

Where $\theta_{1,2,3} = \theta_1 + \theta_2 + \theta_3$.

B. Inverse kinematic problem for SM

Inverse kinematic problem for SM can be solved analytically due to suitable kinematic decomposition. It is clear, see (5) , that the joint coordinate d_1 is given as:

$$\mathrm{d}_1 = \mathrm{X_S}[3,1] \quad (6)$$

The position of the point $\boldsymbol{O}_4$ with respect to the frame F_1 can be expressed from (4):

$$\boldsymbol{O}_4^1 = \begin{bmatrix} L_5\sin(\phi) + \boldsymbol{O}_{e_S}^{0_S}[2,1] - L_1 \\ -L_5\cos(\phi) - \boldsymbol{O}_{e_S}^{0_S}[1,1] \\ 0 \end{bmatrix} \quad (7)$$

Therefore the inverse kinematic problem of the SM is reduced to the solution of the inverse kinematic problem of the planar serial manipulator consisting of the links L_2, L_3, L_4 .

Then the position of the point $\boldsymbol{O}_3$ with respect the frame F_1 is:

$$\boldsymbol{O}_3^1 = \begin{bmatrix} w_x \\ w_y \\ 0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{O}_4^1[1,1] - L_4\cos\phi \\ \boldsymbol{O}_4^1[1,1] - L_4\sin\phi \\ 0 \end{bmatrix} \quad (8)$$

It can be shown that the solution of the joint coordinates θ_1, θ_2 is given by the comparing corresponding elements of the matrix $\prod_{i=2}^{3}\boldsymbol{T}_i^{i-1}(\theta_{i-1})$ and position vector $\boldsymbol{O}_3^1$:

$$\theta_2 = \mathrm{atan2}(\sin\theta_2, \cos\theta_2) \quad (9)$$

Where:

$$\cos\theta_2 = \frac{w_x^2 + w_y^2 - L_2^2 - L_3^2}{2L_2L_3}$$
$$\sin\theta_2 = \pm\sqrt{1-\cos^2\theta_2}$$

And:

$$\theta_1 = \mathrm{atan2}(\sin\theta_1, \cos\theta_1) \quad (10)$$

Where:

$$\sin\theta_1 = \frac{-L_3\sin\theta_2 w_x + (L_2 + L_3\cos\theta_2)w_y}{w_x^2 + w_y^2}$$
$$\cos\theta_1 = \frac{(L_2 + L_3\cos\theta_2)w_x + L_3\sin\theta_2 w_y}{w_x^2 + w_y^2}$$

It is clear, see Fig. 2, that the joint coordinate θ_3 is given as:

$$\theta_3 = \phi - \theta_1 - \theta_2 \quad (11)$$

C. Inverse kinematic problem for PM

The joint and generalized coordinates of the PM are, see Fig. 3.

$$\boldsymbol{\Theta}_P = \begin{bmatrix} l_1 & l_2 & l_3 \end{bmatrix}^T, \boldsymbol{X}_P = \begin{bmatrix} \alpha & \beta & \gamma \end{bmatrix}^T \quad (12)$$

Where $l_i = \|B_iC_i\|$ is an extension of the linear actuators, l_0 is an extension of the linear actuators for the PM's home position ($l_i = l_0$) and α, β, γ are the Euler angles of the end-effector.

The rotation matrix of the end-effector frame with respect to the base frame is:

$$\boldsymbol{R}_{e_P}^{0_P} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix} \cdot \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{bmatrix} \cdot \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (13)$$

The positions of each of the kinematic chains $B_iC_iD_i$ is represented by the position vector $\overrightarrow{B_iD_i}^{0P} = \begin{bmatrix} bd_{ix} \; bd_{iy} \; bd_{iz} \end{bmatrix}^T$ with respect to the base frame:

$$\begin{bmatrix} bd_{1x} \\ bd_{1y} \\ bd_{1z} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{6}a_1 \\ -\frac{1}{2}a_1 \\ v \end{bmatrix} + \boldsymbol{R}_{e_P}^{0_P} \begin{bmatrix} \frac{\sqrt{3}}{6}a_2 \\ \frac{1}{2}a_2 \\ 0 \end{bmatrix}$$
$$\begin{bmatrix} bd_{2x} \\ bd_{2y} \\ bd_{2z} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{6}a_1 \\ \frac{1}{2}a_1 \\ v \end{bmatrix} + \boldsymbol{R}_{e_P}^{0_P} \begin{bmatrix} -\frac{\sqrt{3}}{3}a_2 \\ 0 \\ 0 \end{bmatrix} \quad (14)$$
$$\begin{bmatrix} bd_{3x} \\ bd_{3y} \\ bd_{3z} \end{bmatrix} = \begin{bmatrix} -\frac{\sqrt{3}}{3}a_1 \\ 0 \\ v \end{bmatrix} + \boldsymbol{R}_{e_P}^{0_P} \begin{bmatrix} \frac{\sqrt{3}}{6}a_2 \\ -\frac{1}{2}a_2 \\ 0 \end{bmatrix}$$

Then the joint coordinates are computed from the equation describing the constant length vector $\overrightarrow{C_i D_i}$:

$$\overrightarrow{\boldsymbol{C}_i\boldsymbol{D}_i}^{0_P} = \begin{bmatrix} bd_{ix} & bd_{iy} & bd_{iz} - l_i \end{bmatrix}^T$$
$$\|\overrightarrow{\boldsymbol{C}_i\boldsymbol{D}_i}^{0_P}\|^2 = bd_{ix}^2 + bd_{iy}^2 + (bd_{iz} - l_i)^2 = l^2 \quad (15)$$

Therefore:

$$l_i = bd_{iz} \mp \sqrt{l^2 - bd_{ix}^2 - bd_{iy}^2}, \quad i = 1 \dots 3 \quad (16)$$

D. Forward kinematic problem for PM

Denote the solution of the inverse kinematic problem of PM as:

$$\boldsymbol{\Theta}_P = \boldsymbol{G}_P(\boldsymbol{X}_P) \quad (17)$$

Where $\boldsymbol{G_P}(\boldsymbol{X_P})$ is a nonlinear vector function and it can be shown that there is no analytical solution for generalized coordinates $\boldsymbol{X_P}$. Therefore some numerical methods have to be exploited [4]. The main idea is to find the dynamic system for generalized coordinates $\boldsymbol{X_P}$ which is actuated by the measured values of the joint coordinates $\boldsymbol{\Theta}_{Pm}$ and leads to the linear asymptotically stable error system.

It can be shown that a choice:

$$\dot{\boldsymbol{X}}_P = \boldsymbol{J}_P(\boldsymbol{X}_P)\left[\dot{\boldsymbol{\Theta}}_{P_m} + K[\boldsymbol{\Theta}_{P_m} - \boldsymbol{G}_P(\boldsymbol{X}_P)]\right] \quad (18)$$

Where $\boldsymbol{J}_P^{-1}(\boldsymbol{X_P})$ is an inverse jacobian:

$$\boldsymbol{J}_P^{-1}(\boldsymbol{X}_P) = \begin{bmatrix} \frac{\left(\overrightarrow{\boldsymbol{O}_{e_P}\boldsymbol{D}_1}^{0_P} \times \overrightarrow{\boldsymbol{C}_1\boldsymbol{D}_1}^{0_P}\right)^T}{bd_{1z} - l_1} \\ \dots\dots\dots\dots \\ \frac{\left(\overrightarrow{\boldsymbol{O}_{e_P}\boldsymbol{D}_2}^{0_P} \times \overrightarrow{\boldsymbol{C}_2\boldsymbol{D}_2}^{0_P}\right)^T}{bd_{2z} - l_2} \\ \dots\dots\dots\dots \\ \frac{\left(\overrightarrow{\boldsymbol{O}_{e_P}\boldsymbol{D}_3}^{0_P} \times \overrightarrow{\boldsymbol{C}_3\boldsymbol{D}_3}^{0_P}\right)^T}{bd_{3z} - l_3} \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & \sin\beta \\ 0 & \cos\alpha & -\sin\alpha\cos\beta \\ 0 & \sin\alpha & \cos\alpha\cos\beta \end{bmatrix}$$
$$\overrightarrow{\boldsymbol{O}_{e_P}\boldsymbol{D}_1}^{0_P} = \boldsymbol{R}_{e_P}^{0_P}\begin{bmatrix} \frac{\sqrt{3}}{6}a_2 & \frac{1}{2}a_2 & 0 \end{bmatrix}^T$$
$$\overrightarrow{\boldsymbol{O}_{e_P}\boldsymbol{D}_2}^{0_P} = \boldsymbol{R}_{e_P}^{0_P}\begin{bmatrix} -\frac{\sqrt{3}}{3}a_2 & 0 & 0 \end{bmatrix}^T$$
$$\overrightarrow{\boldsymbol{O}_{e_P}\boldsymbol{D}_3}^{0_P} = \boldsymbol{R}_{e_P}^{0_P}\begin{bmatrix} \frac{\sqrt{3}}{6}a_2 & -\frac{1}{2}a_2 & 0 \end{bmatrix}^T$$
$$\overrightarrow{\boldsymbol{C}_i\boldsymbol{D}_i}^{0_P} = \begin{bmatrix} bd_{ix} & bd_{iy} & bd_{iz} - l_i \end{bmatrix}^T$$

and bd_{ix}, bd_{iy}, bd_{iz}, l_i, $\boldsymbol{R}_{eP}^{0P}$ are known from the inverse kinematic problem of the PM.

Equation (18) can be transform to the following error system:

$$\dot{\boldsymbol{e}} + \boldsymbol{K}\boldsymbol{e} = 0 \quad \text{where} \quad \boldsymbol{e} = \boldsymbol{\Theta}_{Pm} - \boldsymbol{G}_P(\boldsymbol{X}_P) \quad (19)$$

If $\boldsymbol{K}$ is negative definite matrix then the error $\boldsymbol{e}$ converges to zero asymptotically, $\boldsymbol{G}_P(\boldsymbol{X}_P)$ converges to $\boldsymbol{\Theta}_{Pm}$ and $\boldsymbol{X}_P$ converges to the actual end-effector position.

Final forward kinematic problem algorithm is given by the discretization of the equation (19) (discretization step h and a substitution $\boldsymbol{\Theta}_{Pm} \rightarrow \boldsymbol{\Theta}_P$):

$$\boldsymbol{X}_{P_{k+1}} = \boldsymbol{X}_{P_k} + h \cdot \boldsymbol{J}_P(\boldsymbol{X}_{P_k})\left[\dot{\boldsymbol{\Theta}}_P + K[\boldsymbol{\Theta}_P - \boldsymbol{G}_P(\boldsymbol{X}_{P_k})]\right]$$

III. MOTION PLANNING AND CONTROL

Three different coordinate systems are being used for description of the robot motions. **Product coordinate system (PCS)** is a Cartesian system which is defined with respect to a machine part which interacts with the robot and can be used for simple description of the desired trajectory of motion independently on the actual robot configuration. It can be placed in the center of the chambers in order to define the desired motion during the cleaning process (e.g. positioning of the cleaned part with respect to the washing jets). **Machine or base coordinate systems (MCS)** is firmly coupled with a stationary base of the manipulator and defines an operational space of the robot end-effector via the coordinates for position and orientation. The desired motion of the effector is fully described in this system. The relation between PCS and MCS can be formulated by a Cartesian transformation and the operations of translation and rotation. **Axes coordinate system (ACS)** describes the motion of each individual axis of the robot in terms of its position, velocity and acceleration. Every movement defined in the MCS needs to be translated into ACS using the kinematical transformations presented in the previous chapter in order to synchronize the motion of all the axes and track the desired movement correctly.

There are two basic types of admissible motions. **Point-to-point (PTP)** is a movement between two positions in the product or machine coordinates space. The target position should be reached as fast as possible and the path of the end-effector during the motion is arbitrary. This leads to a problem of time optimal control of each individual axis of the robot with respect to kinematical constraints on physically feasible velocity and acceleration. Any rapid movement can excite oscillatory modes of the mechanical construction which results in unwanted residual vibrations of the machine. To avoid this, also the acceleration derivative (jerk) should be limited. Therefore we use a jerk-limited motion planning algorithm to compute a desired trajectory for each axis [5]. The motions can be scaled in time in order to synchronize the arrival to the target position for all the robot axes with respect to the slowest one.

Continuous path (CP) motions are performed using prescribed trajectory in space which the effector has to follow. We support linear, circular and NURBS (nonuniform rational B-spline) interpolation [6]. Every trajectory in the operational space is internally represented in a parametric form which describes the path of the effector in space. However, for the real-time motion planning also a *time path* of the trajectory needs to be computed. This takes place in *feedrate controller* which evaluates the feed along the desired trajectory with respect to maximum velocity, acceleration and jerk.

IV. Structure of the Control System

The motion planning algorithms are implemented in industrial PC (IPC) where real time control system REX which is being developed at our department is installed [7]. The computed reference trajectory is transformed from MCS/PCS into ACS using the kinematical transformations and sent to the servo-inverters of each robot axis via fast industrial ethernet network with EtherCAT protocol [8]. Permanent magnets synchronous motors are used as actuators. The inverters use common cascade structure with feedback loops for current, speed and position control. Field oriented control and space vector modulation techniques are used for current control, the velocity and position loops use standard linear PID controllers. The inverter control system runs with update rate of 16 kHz, the motion planning level in the IPC at 2 kHz. The overall structure of the control system can be seen on Fig. 5.

V. Conclusion

The paper presents newly developed industrial robotic manipulator for degreasing and paint removing lines. Kinematical analysis, motion planning and control algorithms are described.

Currently the research project is in the phase of computer simulations and operational testing of drives and control system hardware. The fully functional prototype of the machine is to be built this year.

Acknowledgment

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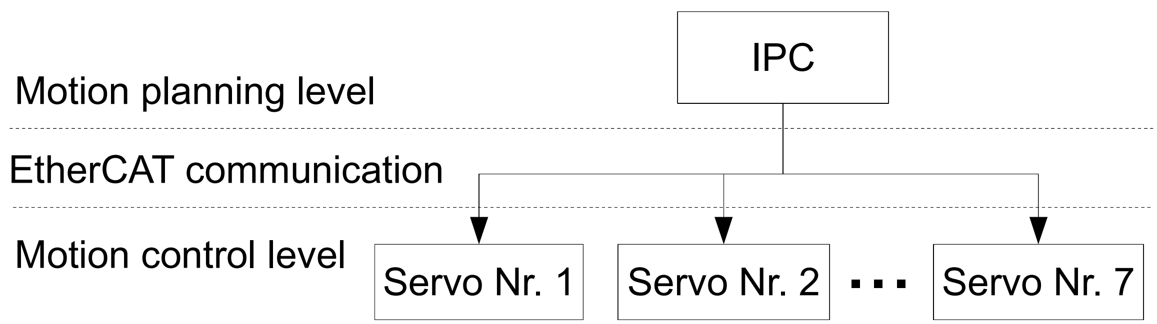

Figure 5. Structure of the control system