Industrial Robots used in Forges Applications

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Abstract. Industrial robots are used especially in sectors where the human body is in danger or is working in extreme conditions. One of these sectors is the forges sector where the manipulating objects are hot, and the vibrations and noise are big. The problem of manipulation the hot parts implies the choosing of the right gripper mechanism in order to obtain the best cooling of it and of the robot itself. The cooling of gripper and robot is realized in the movement phase when no hot payload is present. So, the trajectory of movement is important and also the optimum position of robot with respect to the application positions. The proposed paper is dealing with the subject of moving the base of robot with respect to the application points so that an objective function representing the accumulated heat during a cycle to be minim.

Keywords. Industrial Robot, Forge, Optimum Position

1. Introduction

Industrial robots are used especially in sectors where the human body is in danger or is working in extreme conditions. One of these sectors is the forges sector where the manipulating objects are hot, and the vibrations and noise are big. The problem of manipulation the hot parts implies firstly the choosing of the right gripper mechanism in order to obtain the best cooling of it and of the robot itself. In papers (Simionescu and Ciupitu, 2004) and (Simionescu et al., 2008) grippers with 2 DOF are presented and could be used as well. But the position of robot with respect to the application, by taken into consideration the accumulated heat from work piece during the manipulation of it as an objective function, it is also a very important problem.

An empiric solution of determining the position of robot base by computing only the three coordinates of the origin of the Cartesian coordinate system assigned to the robot base is given in (Kovacs and Cojocaru, 1982.). This empiric solution is not taken into consideration the way of moving of robot between the application points but is taken into consideration the weight of object (tool) that the robot is moving between these. The proposed solution is not demonstrated by any mechanical and mathematical reasons.

In (Tian and Collins, 2005) an optimization problem of placement of a simple two-link planar manipulator by using a genetic algorithm is presented. Also in paper (Mitsi et al., 2008) a hybrid genetic algorithm is used in order to determine the optimum location of the base of robot with respect to imposed discrete positions of end-effector.

The location of robot base with respect to the application is chosen so that all the interest point of application to be situated in the working space of robot. An optimization of this location by taken into consideration the minimum time of movement was presented in papers (Feddema, 1996) and (Ciupitu and Simionescu, 2007). In paper (Ciupitu et al., 2008) an optimum synthesis of motion law together with minimum time of motion was performed. In paper (Ciupitu and Ivanescu, 2010) the problem of optimal location of an industrial robot used in a forge application were formulated.

The mechanical structure of the industrial robot chosen by the manufacturers (for examples: Renault from France and Rahm from Italy), that are using it in forges sector, is of articulate kind with 6 DOF. Sometime the opening area of forge makes difficult the inserting of hot part inside the forge even with 6 DOF. But an industrial robot with a mechanical structure of cylindrical type with at least 5 DOF may solve the problem too. Anyway the gripper used in such an application should have a special shape with long fingers in order to dissipate the heat accumulated from manipulating part.

2. Forging Manufacturing Process

Usually the forged pieces are inserted from a bunker into a furnace in order to be heated (Fig. 1). The hot part comes out from a medium frequency furnace with a random orientation or that can be fixed by special mechanisms, depending of the shape of part. But because of high temperature of part the individualization and orientation of part is difficult to be made with a good accuracy. So, a vision system to recognize the position of part and to communicate with the robot controller (Fig. 2) in order to make the position and orientation corrections of picking configuration, is necessary. (Ciupitu et al., 2009).

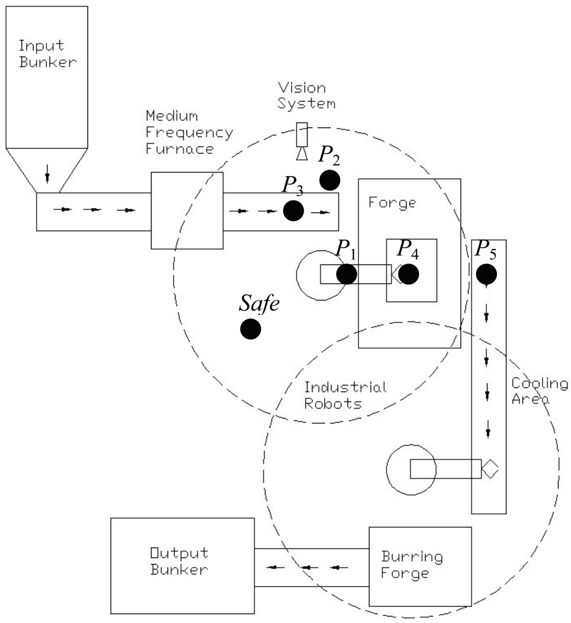


Fig. 1 Application scheme

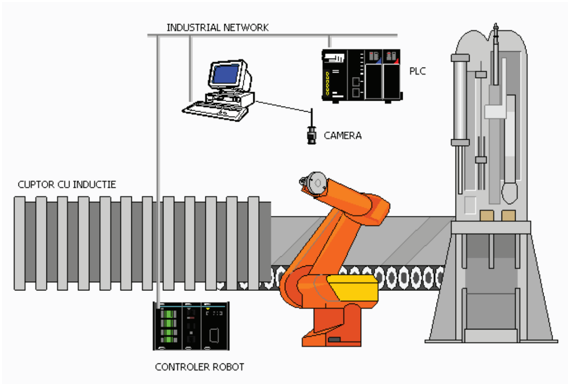
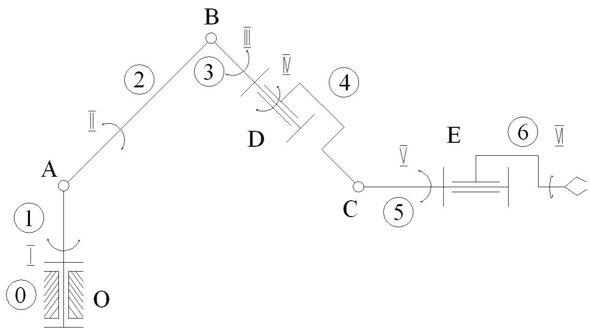


Fig. 2 Communication scheme

From delivering port of furnace the part is inserted by lateral into the forge and left down inside the forging mold. The inserting window is relatively small and requires a long link 6 (Fig. 3) or long gripper fingers.



Sometimes another task of spraying the parts of forge is done by the same robot with the aid of a special dose fixed to the robot arm or to the gripper. Anyway, the different planes in which the pick-and-place are done, and the small window of forge where the robot arm must be inserted, impose a 6 DOF spatial mechanism for robot mechanism.

Fig. 3 Articulate industrial robot with 6 DOF

An industrial robot with a mechanical structure of cylindrical type with at least 5 DOF (Fig. 4) may solve the problem too, but the translatoral joints are pretentiously even in case of cold manufacturing processes.

Actuating system is electric one for robot and pneumatic one for its gripper. The end-effector could be cooled by the aid of a fan or by pressure air in some situations when the temperature of manipulating part is high and the heat cannot be eliminated by the movement of the robot during one cycle.

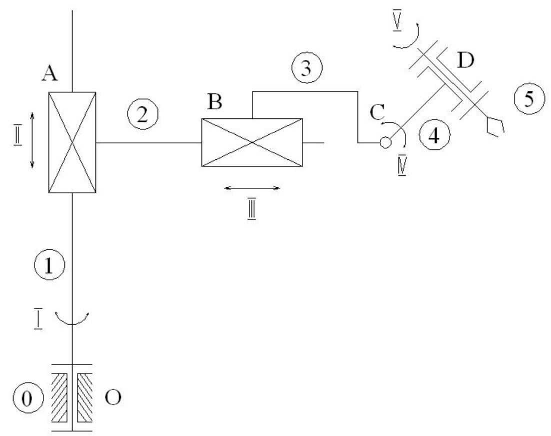


Fig. 4 Cylindrical industrial robot with 5 DOF

The same inserting mode is used to put the work piece into the burring forge (Fig. 1). That can be done by another robot or by a human operator, but the work piece should be cold enough to not be deformed when the burring is done. So, a cooling area is interposed between main forge and burring forge, by using some fans. The transfer from main forge to the conveyer can be done by first robot or by the forge mechanism itself.

Finally the forged piece is directed to another bunker and transported to another manufacturing cell.

3. Optimisation Problem

In order to formulate the optimization problem 2 models must to be known:

- the mechanical structure model of robot with minimum and maximum acceptable values for each joint independent parameter and
- the forge application given by: coordinates of positions (configurations) that the robot must reach, the trajectories and motion laws between these points, the temperature of work pieces and the weight of them.

3.1. Robot Mechanism Model

Usual the mechanical structure model of a robot is implemented in robot controller by using Denavit-Hartenberg formalism in order to find a transformation from tool tip to the base of robot. The matrix transformation of coordinates of a point P expressed in a $O_{i+1}X_{i+1}Y_{i+1}Z_{i+1}$ coordinates system to coordinates of the same point in another $O_iX_iY_iZ_i$ coordinates system is:

$$\mathbf{A}_i = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ a_i\cos\theta_i & \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i \\ a_i\sin\theta_i & \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i \\ s_i & 0 & \sin\alpha_i & \cos\alpha_i \end{Vmatrix}$$

By choosing the axes systems in a special manner, the number of unknown parameters between 2 Cartesian coordinates systems chosen anyway on each link is reduced from six to four:

- a_i - the length of common perpendicular measured from O_iZ_i axis to $O_{i+1}Z_{i+1}$ axis;
- s_i - the distance between O_iX_i and $O_{i+1}X_{i+1}$ axes, measured upon O_iZ_i axis;
- α_i - angle between O_iZ_i and $O_{i+1}Z_{i+1}$ axes, measured around X_{i+1} axis;
- θ_i - angle between O_iX_i and $O_{i+1}X_{i+1}$ axes, measured around O_iZ_i axis.

For example for a robot mechanism with an open chain with 6 mobile links (Fig. 2), the coordinates transformation of a point P_j from $O_7X_7Y_7Z_7$ axes system attached to the end-effector and the coordinates in base system $O_1X_1Y_1Z_1$ could be write as follow (Simionescu and Ciupitu 2007):

$$\begin{Vmatrix} 1 \\ X_{1P_j} \\ Y_{1P_j} \\ Z_{1P_{ji}} \end{Vmatrix} = \mathbf{A}_1\ \mathbf{A}_2\ \mathbf{A}_3\ \mathbf{A}_4\ \mathbf{A}_5\ \mathbf{A}_6 \begin{Vmatrix} 1 \\ X_{7P_j} \\ Y_{7P_j} \\ Z_{7P_j} \end{Vmatrix} \quad (1)$$

3.2. Forge Application Model

The model of forge application is simplified composed only by the 5 points P_j , $j = \overline{1,\ 5}$, that the robot must reach during the motion, without any obstacles defined (excluding the robot itself):

P_1 - in front of forge (waiting point);
P_2 - upper of the picking position;
P_3 - picking position from the exit of furnace;
P_4 - inside forge;
P_5 - extreme position of eliminating the piece from forge to the cooling on conveyer.

Also the order of reaching these 5 points in a complete cycle (8 intervals of motion: P_1->P_2->P_3->P_2->P_1->P_4->P_1->P_5->P_1) and the motions laws between these are supposed as known.

Usual the robot controllers are implemented with only few motion laws between 2 positions (configurations) from working space: of sinusoidal shape and of parabolic shape (Intelitek, 2003). Transmission functions given numerically, and resulted for example from an optimization process done off-line (Ciupitu et al., 2008), could be used for moving robot to a specific trajectory.

In forge applications, where the work pieces are hot, the temperatures of them and of the environment are influencing the temperature of robot and the precision of it. The heat accumulated by the robot during a cycle depends by the temperature of work piece T and by the time when the work piece is manipulated by the robot. From 8 intervals of motions only in 4 the robot gripper is in contact with hot piece.

Finally, especially for optimization problems that is dealing with forces and energy or power consumption, the weights $\boldsymbol{G}_{jk}$, $j = \overline{1,\ 5}$, $k = \overline{1,\ 5}$, of objects moved by robots between application points must to be known.

3.3. Optimization Problem

In order to start the formulation of optimization problem we have to identify the unknown parameters. The unknowns of optimization problem are the parameters that are defining the position and the orientation of Cartesian coordinates system assigned to the base of robot $O_1X_1Y_1Z_1$ with respect to an inertial Cartesian system assigned to the "world of robot" (or to the application) denoted by $O_0X_0Y_0Z_0$. These parameters are composed by the 3 Cartesian coordinates of origin O_1 expressed in Cartesian system $O_0X_0Y_0Z_0$ (X_{0O1}, Y_{0O1}, Z_{0O1}) and the 3 independent angles that is giving the orientation of Cartesian system assigned to the robot base $O_1X_1Y_1Z_1$ with respect to Cartesian system $O_0X_0Y_0Z_0$ from the cosines directories matrix:

$$\boldsymbol{\alpha} = \begin{Vmatrix} \alpha_{X_0X_1} & \alpha_{X_0Y_1} & \alpha_{X_0Z_1} \\ \alpha_{Y_0X_1} & \alpha_{Y_0Y_1} & \alpha_{Y_0Z_1} \\ \alpha_{Z_0X_1} & \alpha_{Z_0Y_1} & \alpha_{Z_0Z_1} \end{Vmatrix} \tag{2}$$

The number of unknown parameters could be reduced by choosing the Cartesian system $O_0X_0Y_0Z_0$ in a Denavit-Hartenberg manner. So, by choosing the O_0Z_0 axis perpendicular to the O_1X_1 axis (chosen randomly perpendicular to the O_1Z_1 axis), only 4 parameters are enough: a_0, s_0, α_0, θ_0. In this situation the coordinates of application points are constant with respect to the Cartesian system $O_0X_0Y_0Z_0$ and the coordinates transformation equation is:

$$\begin{Vmatrix} 1 \\ X_{0P_j} \\ Y_{0P_j} \\ Z_{0P_{ji}} \end{Vmatrix} = \mathbf{A}_0 \begin{Vmatrix} 1 \\ X_{1P_j} \\ Y_{1P_j} \\ Z_{1P_{ji}} \end{Vmatrix} \tag{3}$$

The known parameters of problem were formulated in previous paragraphs as follow:

- Denavit-Hartenberg parameters: a_i, s_i, α_i, θ_i, $i = \overline{1,\ 6}$;
- Cartesian coordinates of application points: X_{0Pj}, Y_{0Pj}, Z_{0Pj}, $j = \overline{1,\ 5}$;
- trajectories between these points: T_{jk} , $j = \overline{1,\ 5}$, $k = \overline{1,\ 5}$, $j \neq k$;
- maximum speed and maximum acceleration accepted for each driving motor of robot joints: $v_{i\max}$, $a_{i\max}$, $i = \overline{1,\ 6}$ and the other parameters of motions laws that are specifying completely the transmission functions of second degree;
- temperature of working piece: T.
- weights $\boldsymbol{G}_{jk}$, $j = \overline{1,\ 5}$, $k = \overline{1,\ 5}$, $j \neq k$.

The objective function of optimization problem is a sum (or integral) of minimized parameter:

$$\boldsymbol{O} = \sum_{l=1}^{8} Q_l \tag{4}$$

where Q_l is the heat accumulated by the robot in each interval of motion from a cycle.

The heat transfer by conduction between two plane surfaces is given by the following relation:

$$\frac{Q}{t} = \chi A \frac{T_{hot} - T_{cold}}{d} , \tag{5}$$

where:

Q is the heat transfer in time t;

χ is the thermal conductivity of the barrier;

A is area of contact surface;

T_{hot} and T_{cold} are the temperatures of plane surfaces in contact;

d is the thickness of barrier.

The process of finding the optimum set of parameters $\{a_0^*, s_0^*, \alpha_0^*, \theta_0^*\}$ is a numerical one where these parameters are changed during the computation according to a specific algorithm. At the beginning of computation, starting by an initial set $\{a_0^{(0)}, s_0^{(0)}, \alpha_0^{(0)}, \theta_0^{(0)}\}$, a complete verification of application points P_j, $j = \overline{1,\ 5}$ so that to be into working space of robot is performed. This verification implies the computing of coordinates of all application points in $O_1X_1Y_1Z_1$ Cartesian system:

$$\begin{Vmatrix} 1 \\ X_{1P_j}^{(0)} \\ Y_{1P_j}^{(0)} \\ Z_{1P_j}^{(0)} \end{Vmatrix} = \mathbf{A}_0^{-1} \begin{Vmatrix} 1 \\ X_{0P_j} \\ Y_{0P_j} \\ Z_{0P_{ji}} \end{Vmatrix} , j = \overline{1,\ 5}. \tag{6}$$

By inverse kinematics a set of joint independent variables $\{\theta_{1,j}^{(0)}, \theta_{2,j}^{(0)}, \ldots, \theta_{6,j}^{(0)}\}$ is determined for each point P_j, $j = \overline{1,\ 5}$.

A point P_j, $j = \overline{1,\ 5}$ is in working space of robot if all independent variables values are between minimum and maximum acceptable values for each joint:

$$\theta_{i\min} \le \theta_{i,j} \le \theta_{i\max} , i = \overline{1,\ 6}, j = \overline{1,\ 5}. \tag{7}$$

Conditions (7) represent the inequality constrains of optimization problem:

$$\theta_{i\min} - \theta_{i,j} \le 0, i = \overline{1,\ 6}, j = \overline{1,\ 5}, \tag{8}$$

$$\theta_{i,j} - \theta_{i\max} \le 0, i = \overline{1,\ 6}, j = \overline{1,\ 5}. \tag{9}$$

The inequality constrains (8) and (9) can be transformed in equality constrains:

$$h_k = \theta_{i\min} - \theta_{i,j} + w_k^2 = 0,\ i = \overline{1,\ 6}\,,\ j = \overline{1,\ 5}\,, \qquad (8')$$

$$h_{k+30} = \theta_{i,j} - \theta_{i\max} + w_{k+30}^2 = 0,\ k = \overline{1,\ 30}\,, \qquad (9')$$

by introducing the unknown parameters w_l , $l = \overline{1,\ 60}$.

The Lagrange method for solving of the minimization problems is based on transforming a given constrained minimization problem into an unconstrained minimization problem. This operation is accomplished by defining an appropriate auxiliary function, in terms of the problem functions, to define a new objective function whose minima is unconstrained in some domain of interest. The Lagrange function has the next form:

$$\boldsymbol{L} = \boldsymbol{O} + \sum_{l=1}^{60} \lambda_l h_l\,, \qquad (10)$$

where λ_l , $l = \overline{1,\ 60}$ are Lagrange multipliers.

The necessary conditions for the minimizing the Lagrange function are:

$$\frac{\partial \boldsymbol{L}}{\partial a_0} = 0\,,\ \frac{\partial \boldsymbol{L}}{\partial s_0} = 0\,,\ \frac{\partial \boldsymbol{L}}{\partial \alpha_0} = 0\,,\ \frac{\partial \boldsymbol{L}}{\partial \theta_0} = 0\,,$$
$$\frac{\partial \boldsymbol{L}}{\partial w_l} = 0\,,\ \frac{\partial \boldsymbol{L}}{\partial \lambda_l} = 0\,,\ l = \overline{1,\ 60}\,. \qquad (11)$$

The non-linear system composed by equations (11) with 124 unknowns is solved with a proper numerical method. The problem has infinity of solutions according to the initial solution.

4. Conclusions

The optimum location of robot base depends to the robot structure and to the application. With same robot but different application positions and conditions results different locations for robot base.

The problem of finding the optimum location of robot base with respect to the application points according to an objective function is very important and could lead to major improvements (Ciupitu and Simionescu, 2007), (Mitsi et al., 2008). Sometimes the conditions of application impose special adjustments in order to protect the robot. The placing of robot base in an optimum location from the very first beginning is an essential initial task especially for large series productions. The economy of time or/and energy (money finally) for each product is decreasing it's price to almost a quarter (Feddema, 1996) but the protection of industrial robot parts is much more important because without robot no production.

A multi-criterial optimisation by taken into consideration the protection of industrial robot which is working in a hazardous environment and the economy of time and energy is maybe the best solution.

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