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Technical note

On the design of serial manipulators with decoupled dynamics

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ABSTRACT

This paper deals with the problem of dynamic decoupling of serial manipulators via inertia parameter design. The goal is to simplify the controller design by reducing the effects of complicated manipulator dynamics. The added complementary links allow the optimal redistribution of kinetic and potential energies, which leads to the linearization and decoupling of the dynamic equations. The determination of the parameters of the added links is based on eliminating coefficients of nonlinear terms in the manipulator's kinetic and potential energy equations. The proposed decoupling concept is achieved by adding secondary gears and rotation transmissions. The suggested design methodology is illustrated by simulations carried out using the software ADAMS. The proposed solution permits the dynamic decoupling of the serial manipulators with a relatively small increase in the total mass of the moving links. It provides an improvement in the known design solutions, rendering them more suitable for practical applications.

1. Introduction

It is known that the manipulator dynamics are highly coupled and nonlinear. The complicated dynamics results from varying inertia, interactions between the different joints, and nonlinear forces such as Coriolis and centrifugal forces. Nonlinear forces cause errors in position response at high speed, and have been shown to be significant even at slow speed [1]. Thus, improving the positioning accuracy of manipulators via dynamic decoupling needs further development in advanced robotics.

The linearization of dynamic equations of robot mechanisms has attracted researchers' attention and different solutions have been proposed. They can be mentioned by three principal trends:

(a) The linearization of dynamic equations via actuator relocation, i.e. by the kinematic decoupling of motion when the rotation of any link is due to only one actuator [2–10]. In other terms, it should be assumed that the actuator displacements are a complete set of independent generalized coordinates that are able to locate the manipulator uniquely and completely. The design concept with remote actuation is not optimal from point of view of the precise reproduction of the motion because it accumulates all errors due to the clearances and elasticity of the belt transmission, as well as the manufacturing and assembly errors due to the rotation transmission mechanism.

(b) The linearization of dynamic equations via optimum inertia redistribution [11–20], i.e. when the inertia tensors are diagonal and independent of manipulator configuration. Such an approach is efficient for spatial serial manipulators in which the axis of joints are not parallel.

(c) The linearization of dynamic equations via added links [21,22]. The modification of the manipulator structure to achieve high-quality dynamic performance is a new promising tendency in the robot design and it is to pursue the development of new robot mechanisms which can be modeled accurately with little difficulty. However, the design methodology proposed in [21] leads to the unavoidable increase of the total mass of the manipulator due to the disposition of the added elements in the end of each link.

It should be noted that a number of procedures for the synthesis of control systems ensuring high-quality control of manipulators have been elaborated on the basis of the general form of nonlinear dynamic equations [23–32]. However, regardless of the permanent tendency to decrease the price of microcomputer systems, the price of implementation of a complete dynamic control in the case of high-speed and precise dynamical tasks on the industrial practice is still high. Therefore, in many cases, the reduction (or cancellation) of coupling and nonlinearity in the manipulators, as it has been shown in [33–36], is necessary. The known mechanical solutions can only be reached by a considerably complicated design and especially by unavoidable increase to the total mass of the manipulator and as a result, the input torques.

This paper improves the known design concept described in [21] permitting the dynamic decoupling of serial manipulators

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with a relatively small increase in the total mass of the moving links. It is also discussed the dynamic decoupling of 3-DOF spatial manipulator.

2. The improved design methodology

Consider a robot arm composed of n links. According to Lagrangian dynamics, the equations of motion can be written as

$$\tau_i = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i}, \quad i = 1, \ldots, n \tag{1}$$

where τ_i is the generalized torque (or force); θ_i is the generalized coordinate; $L = T - P$ is the Lagrangian; T is the kinetic energy and P is the potential energy.

The kinetic energy of segment i can be expressed as

$$T_i = 0.5 trace\left(\mathbf{V}_i \mathbf{M}_i \mathbf{V}_i^T\right) + 0.5 \boldsymbol{\omega}_i^T \mathbf{I}_i \boldsymbol{\omega}_i \tag{2}$$

in which $\mathbf{M}_i$ and $\mathbf{I}_i$ are the mass and inertia tensors, and $\mathbf{V}_i$ and $\boldsymbol{\omega}_i$ are the translational and angular velocities respectively, which can be expressed as

$$\begin{aligned} V_i &= \sum_{j=1}^{i} f_{ij}^{(V)}(\theta_1, \ldots, \theta_i)\dot{\theta}_i \\ \omega_i &= \sum_{j=1}^{i} f_{ij}^{(\omega)}(\theta_1, \ldots, \theta_i)\dot{\theta}_i \end{aligned} \tag{3}$$

When Eq. (3) is substituted into Eq. (2), we obtain

$$T = \sum_{i=1}^{n} T_i = \sum_{i=1}^{n}\sum_{j=1}^{i}\sum_{k=1}^{i} A_{ijk}(\theta_1, \ldots, \theta_i)\dot{\theta}_j\dot{\theta}_k \tag{4}$$

The potential energy is the function of the generalized coordinates θ_i only, which can be written as

$$P = \sum_{i=1}^{n} f_i^{(P)}(\theta_1, \ldots, \theta_i) \tag{5}$$

By putting Eqs. (4) and (5) into Eq. (1), we get

$$\tau_i = \sum_{j=1}^{n}\sum_{k=1}^{j} A_{ijk}(\theta_1, \ldots, \theta_j)\ddot{\theta}_k + \frac{\sum_{j=1}^{n}\sum_{k=1}^{j}\sum_{i=1}^{j}\partial A_{ijk}(\theta_1, \ldots, \theta_j)}{\partial\dot{\theta}_i\dot{\theta}_j\dot{\theta}_k} - \frac{\sum_{j=1}^{n} f_j^{(P)}(\theta_1, \ldots, \theta_i)}{\partial \theta_i} \tag{6}$$

Thus, we can see that there is nonlinearity in the manipulator dynamics and our goal to develop an improved design concept permitting the dynamic decoupling of serial manipulators.

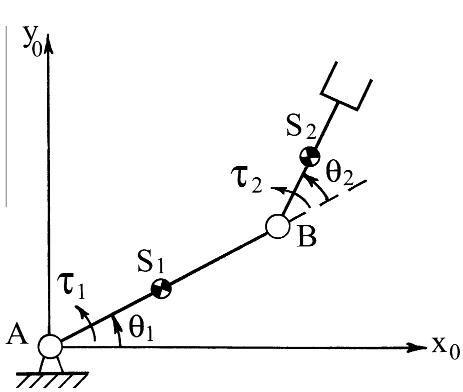

Fig. 1. The 2-DOF planar serial manipulator.

To understand better the suggested design concept let us first consider the dynamic equations for a planar manipulator with two degrees of freedom shown in Fig. 1.

In this case Eq. (6) can be written as

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix}D_{11} & D_{12}\\ D_{21} & D_{22}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix} + \begin{bmatrix}D_{111} & D_{122}\\ D_{211} & D_{222}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1^2\\ \dot{\theta}_2^2\end{bmatrix} + \begin{bmatrix}D_{112} & D_{121}\\ D_{212} & D_{221}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\dot{\theta}_2\\ \dot{\theta}_1\dot{\theta}_2\end{bmatrix} + \begin{bmatrix}D_1\\ D_2\end{bmatrix} \tag{7}$$

with

$$D_{11} = m_1 l_{AS1}^2 + m_2 l_1^2 + m_2 l_{BS2}^2 + 2m_2 l_1 l_{BS2}\cos\theta_2 + I_{S1} + I_{S2} \tag{8}$$

$$D_{12} = D_{21} = m_2 l_{BS2}^2 + m_2 l_1 l_{BS2}\cos\theta_2 + I_{S2} \tag{9}$$

$$D_{22} = m_2 l_{BS2}^2 + I_{S2} \tag{10}$$

$$D_{111} = 0 \tag{11}$$

$$D_{122} = -m_2 l_1 l_{BS2}\sin\theta_2 \tag{12}$$

$$D_{211} = m_2 l_1 l_{BS2}\sin\theta_2 \tag{13}$$

$$D_{222} = 0 \tag{14}$$

$$D_{112} = D_{121} = -m_2 l_1 l_{BS2}\sin\theta_2 \tag{15}$$

$$D_{212} = D_{221} = 0 \tag{16}$$

$$D_1 = (m_1 l_{AS1} + m_2 l_1)g\cos\theta_1 + m_2 g l_{BS2}\cos(\theta_1 + \theta_2) \tag{17}$$

$$D_2 = m_2 g l_{BS2}\cos(\theta_1 + \theta_2) \tag{18}$$

where l_1, l_2 are the lengths of links 1 and 2; θ_1 is the angular displacement of link 1 relative to the base; θ_2 is the angular displacement of link 2 relative to link 1; $\dot{\theta}_1$ is the angular velocity of link 1 relative to the base; $\dot{\theta}_2$ is the angular velocity of link 2 relative to link 1; m_1, m_2 are the masses of links 1 and 2; l_{AS1} is the distance between the center of mass S_1 of link 1 and joint center A; l_{BS2} is the distance between the center of mass S_2 of link 2 and joint center B, I_{S1} is the axial moment of inertia of link 1 relative to the center of mass $S1$ of link 1; I_{S2} is the axial moment of inertia of link 2 relative to the center of mass $S2$ of link 2; g is the gravitational acceleration.

There are two intrinsic problems involved in Eq. (7) regarding the manipulator dynamics: complexity and nonlinearity. The proposed design methodology described bellow will eliminate both the complexity and the nonlinearity. Notice that the suggested method is more efficient from point of view of the mass increasing of the manipulator.

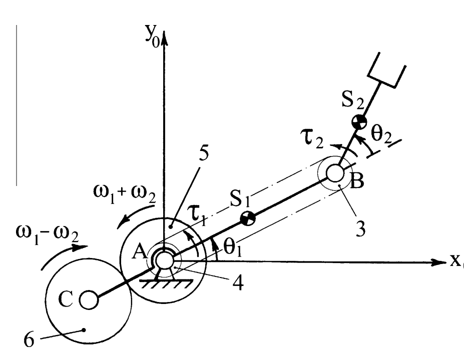

Fig. 2. Design of the decoupled 2-DOF planar serial manipulator.

2.1. Design of decoupled 2-DOF planar serial manipulator

The proposed 2-DOF manipulator illustrated in Fig. 2 differs from the traditional scheme by the fact that two counter rotating links 5 and 6 are mounted on actuated element 1 and linked kinematically with second actuated element 2 through a belt transmission. It should be noted that a similar architecture with relocated counterweights has also been proposed in [21].

Let us rewrite the Lagrangian of the manipulator with the added links:

$$L = K - P = \sum_{i=1}^{6} K_i - \sum_{i=1}^{6} P_i = 0.5\left(m_1 V_{S1}^2 + m_2 V_{S2}^2 + m_3 V_B^2 + m_6 V_C^2\right) + 0.5\left[I_{S1}\dot\theta_1^2 + (I_{S2} + I_{S3} + I_{S4} + I_{S5})(\dot\theta_1 + \dot\theta_2)^2 + I_{S6}(\dot\theta_1 - \dot\theta_2)^2\right] - \sum_{i=1}^{6} P_i = 0.5\left[(k_1 + 2k_2\cos\theta_2)\dot\theta_1^2 + k_3\dot\theta_2^2 + (k_4 + 2k_2\cos\theta_2)\dot\theta_1\dot\theta_2\right] - k_5\sin\theta_1 - k_6\sin(\theta_1 + \theta_2) \quad (19)$$

where

$$k_1 = m_1 l_{AS1}^2 + m_2\left(l_1^2 + l_{BS2}^2\right) + m_3 l_1^2 + m_6 l_{AC}^2 + I_{S1} + I_{S2} + I_{S3} + I_{S4} + I_{S5} + I_{S6} \quad (20)$$

$$k_2 = m_2 l_1 l_{BS2} \quad (21)$$

$$k_3 = m_2 l_{BS2}^2 + I_{S2} + I_{S3} + I_{S4} + I_{S5} + I_{S6} \quad (22)$$

$$k_4 = 2(k_3 - 2I_{S6}) \quad (23)$$

$$k_5 = (m_1 l_{AS1} + m_2 l_1 + m_3 l_1 - m_6 l_{AE})g \quad (24)$$

$$k_6 = m_2 l_{BS2} g \quad (25)$$

The static balancing of the manipulator lead to the condition:

$$k_2 = k_5 = k_6 = 0 \quad (26)$$

and

$$L = 0.5\left(k_1\dot\theta_1^2 + k_3\dot\theta_2^2 + k_4\dot\theta_1\dot\theta_2\right) \quad (27)$$

Thus, if $I_{S6} = 0.5k_3$, i.e. $k_4 = 0$, we obtain $L = 0.5\left(k_1\dot\theta_1^2 + k_3\dot\theta_2^2\right)$ and consequently

$$\tau_1 = k_1\ddot\theta_1 \quad (28)$$

and

$$\tau_2 = k_3\ddot\theta_2 \quad (29)$$

Now let us disclose the advantages of such a design: (i) gear 5 is mounted on the frame, which allows the reduction of the balancing masses; (ii) gear 6 is mounted on the prolongation of link 1, which allows the use of the mass of gear 6 designed for dynamic linearization as a counterweight for static balancing of link 1. Such a solution allows the considerable reduction of the total masses of links of the decoupled manipulator.

As it was mentioned in the introduction, the dynamic decoupling of the degrees of freedom of a manipulator can be achieved by a remote actuation, i.e. when the actuator of the second link of the examined manipulator is mounted on the base and it is coupled with the link via a belt transmission. The schematics of the suggested design concept and the design with remote actuation are almost similar. However, the manipulator with remote actuation is not effective the from point of view of the precise reproduction of the motion as it accumulates all errors due to the clearances and elasticity of the belt transmission, as well as the manufacturing and assembly errors due to the rotation transmission mechanism. In the case of the suggested design concept the actuators are located in the axes A and B but thanks to the added gears and the belt transmission the dynamic equations of the manipulator are decoupled.

It is obvious that the proposed design can be used not only for the 2-DOF planar serial manipulators but also for any multi-degree-of-freedom spatial serial manipulator. In the case of the spatial manipulators the suggested technique will take into account that the inertia tensor of the manipulator must be diagonal and independent of arm configuration [11].

Let us consider the dynamic linearization of a 3-DOF spatial serial manipulator.

2.2. Design of decoupled 3-DOF spatial serial manipulator

In the case of the 3-DOF spatial serial manipulator (Fig. 3) two rotating gears 7 and 8 are mounted on the second link of the manipulator and coupled with gear 6 linked with third link through a belt transmission.

It should be noted that for invariant inertia of any spatial serial manipulator there is the condition concerning the identical inertias of transverse direction, i.e. $I_x = I_y$ (see in [12]). Taking into account that in the examined spatial manipulator there are the links with masses m_2, m_3, m_7 and m_8, it is necessary that this condition will also be satisfied for these masses. Thus, the inertias of transverse direction will be identical, i.e. $I_m = I_{(m_i)x_2} = I_{(m_i)y_2}$. The kinetic energy of these masses relative to the z_1 axis can be presented as $K_m = I_{(m_i)z_1}\dot\theta_1^2 = cI_m\dot\theta_1^2$, i.e. $I_{(m_i)z_1}$ can be replaced by the inertia cI_m, where c is a constant.

Thus, the Lagrangian of the statically balanced manipulator with the mentioned identical inertias of transverse direction of masses m_2, m_3, m_7 and m_8 ($I_m = I_{(m_i)x_2} = I_{(m_i)y_2}$) [12], can be written as:

$$L = 0.5\left[I_{z_1}\dot\theta_1^2 + cI_m\dot\theta_1^2 + I_m\dot\theta_2^2 + I_{x_2}\dot\theta_1^2\sin^2\theta_2 + I_{y_2}\dot\theta_1^2\cos^2\theta_2 + I_{z_2}\dot\theta_2^2 + I_{x_3}\dot\theta_1^2\sin^2(\theta_2+\theta_3) + I_{y_3}\dot\theta_1^2\cos^2(\theta_2+\theta_3) + I_{z_3}(\dot\theta_2+\dot\theta_3)^2 + (I_{z_7} + I_{z_8})(\dot\theta_2 - \dot\theta_3)^2\right] = 0.5\left[p_1\dot\theta_1^2 + p_2\dot\theta_2^2 + p_3\dot\theta_3^2 + p_4\dot\theta_1\dot\theta_2\right] \quad (30)$$

with

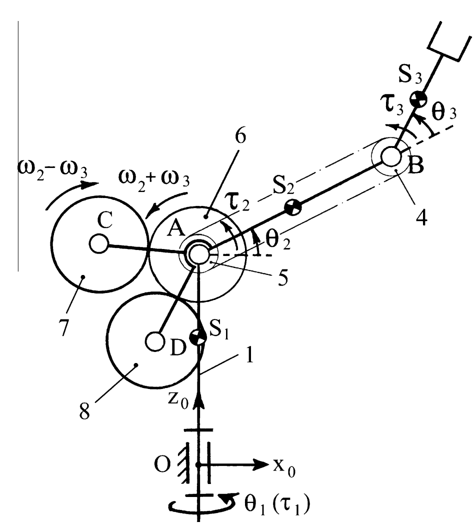

Fig. 3. Design of the decoupled 3-DOF spatial serial manipulator.

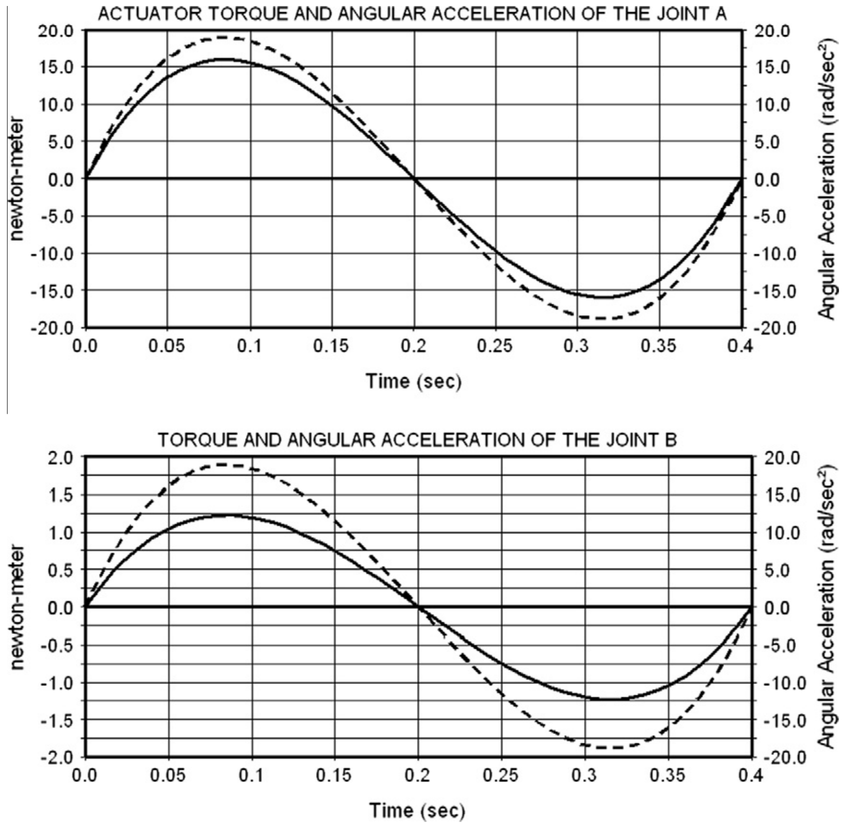

Fig. 4. Actuator torques (solid line) and angular accelerations (dashed line) for 2-DOF linearized manipulator.

$$p_1 = I_{z_1} + cI_m + I_{x_2}\sin^2\theta_2 + I_{y_2}\cos^2\theta_2 + I_{x_3}\sin^2(\theta_2+\theta_3) + I_{y_3}\cos^2(\theta_2+\theta_3) \quad (31)$$

$$p_2 = I_m + I_{z_2} + I_{z_3} + I_{z_7} + I_{z_8} \quad (32)$$

$$p_3 = I_{z_3} + I_{z_7} + I_{z_8} \quad (33)$$

$$p_4 = 2(I_{z_3} - I_{z_7} - I_{z_8}) \quad (34)$$

where I_{z_i} is the inertia of axial direction, I_{x_i} and I_{y_i} are the inertia of transverse directions with respect to the mass center of link i ($i = 1, 2, 3$); θ_1 is the angular displacement of link 1 relative to the base; θ_2 is the angular displacement of link 2 relative to link 1; θ_3 is the angular displacement of link 3 relative to link 2; $\dot{\theta}_1$ is the angular velocity of link 1 relative to the base; $\dot{\theta}_2$ is the angular velocity of link 2 relative to link 1; $\dot{\theta}_3$ is the angular velocity of link 3 relative to link 2; c is a constant due to the distribution of masses m_2, m_3, m_7 and m_8 according to the mentioned condition of identical inertia about transverse directions.

From Eqs. (31) and (34) we can see that the manipulator dynamics will be decoupled if

$$I_{x_2} = I_{y_2} \quad (35)$$

$$I_{x_3} = I_{y_3} \quad (36)$$

$$I_{z_3} = I_{z_7} + I_{z_8} \quad (37)$$

By assuming these conditions, the kinetic energy of the manipulators will be constant and consequently

$$\tau_1 = p_1\ddot{\theta}_1 \quad (38)$$

$$\tau_2 = p_2\ddot{\theta}_2 \quad (39)$$

$$\tau_3 = p_3\ddot{\theta}_3 \quad (40)$$

Thus, the dynamic decoupling is again achieved.

In order to evaluate the dynamic performance of the improved design methodology let us consider a few illustrative examples.

3. Illustrative examples

For illustration of the performance of the suggested design methodology, the simulations using ADAMS software have been carried out for a 2-DOF and 3-DOF serial manipulators. The manipulator parameters of the 2-DOF serial manipulator (Fig. 2) are the following: m_1 = 2.5 kg; m_2 = 2 kg; m_5 = 1 kg; m_6 = 6.5 kg; l_1 = 0.4 m; l_{AS1} = 0.2 m; l_{BS2} = 0; I_{S1} = 0.1 kg m; I_{S2} = 0.0275 kg m; I_{S5} = 0.005 kg m; I_{S5} = 0.0325 kg m. The generation of motions between the initial and final positions of links: θ_{1I} = 0; θ_{1F} = 0.5236; θ_{1F} = 0.5236; θ_{2I} = 1.0472 and θ_{2F} = 1.5708, are carried out by the following fifth order polynomial laws: $\theta_j = 5.2360t^3 - 7.8540t^4 + 3.1416t^5$ ($j = 1, 2$), $0 \leqslant t \leqslant 0.4$ s.

Fig. 4 shows the variations of the input torques and accelerations. We can see that the dynamic equations are linearized, i.e. $\tau_1 = k_1\ddot{\theta}_1$ and $\tau_2 = k_3\ddot{\theta}_2$.

It should be also noted that the decoupled manipulator designed according to schematics proposed in [21] and having the same overall dimensions will be more than two times heavier.

Let us now consider the dynamic decoupling of the 3-DOF spatial serial manipulator (Fig. 3). The manipulator parameters are the following: m_1 = 4 kg; m_2 = 2.5 kg; m_3 = 2 kg; m_6 = 1 kg; m_7 = 6.5 kg; m_8 = 6.5 kg; $l_{AB} = l_2$ = 0.4 m; l_{AS2} = 0.2 m; l_{BS3} = 0; $l_{AC} = l_{AD}$ = 0.5612 m; $\angle BAC = \angle BAD = 125^\circ$; I_{z1} = 0.0125 kg m; I_{z2} = 0.1 kg m; $I_{x2} = I_{y2}$ = 0.0175 kg m; I_{z3} = 0.0275 kg m; $I_{x3} = I_{y3}$ = 0.01 kg m; I_{z5} = 0.005 kg m; $I_{z7} = I_{z8}$ = 0.01625 kg m. The generation of motions between the initial and final positions of links: θ_{1I} = 0;

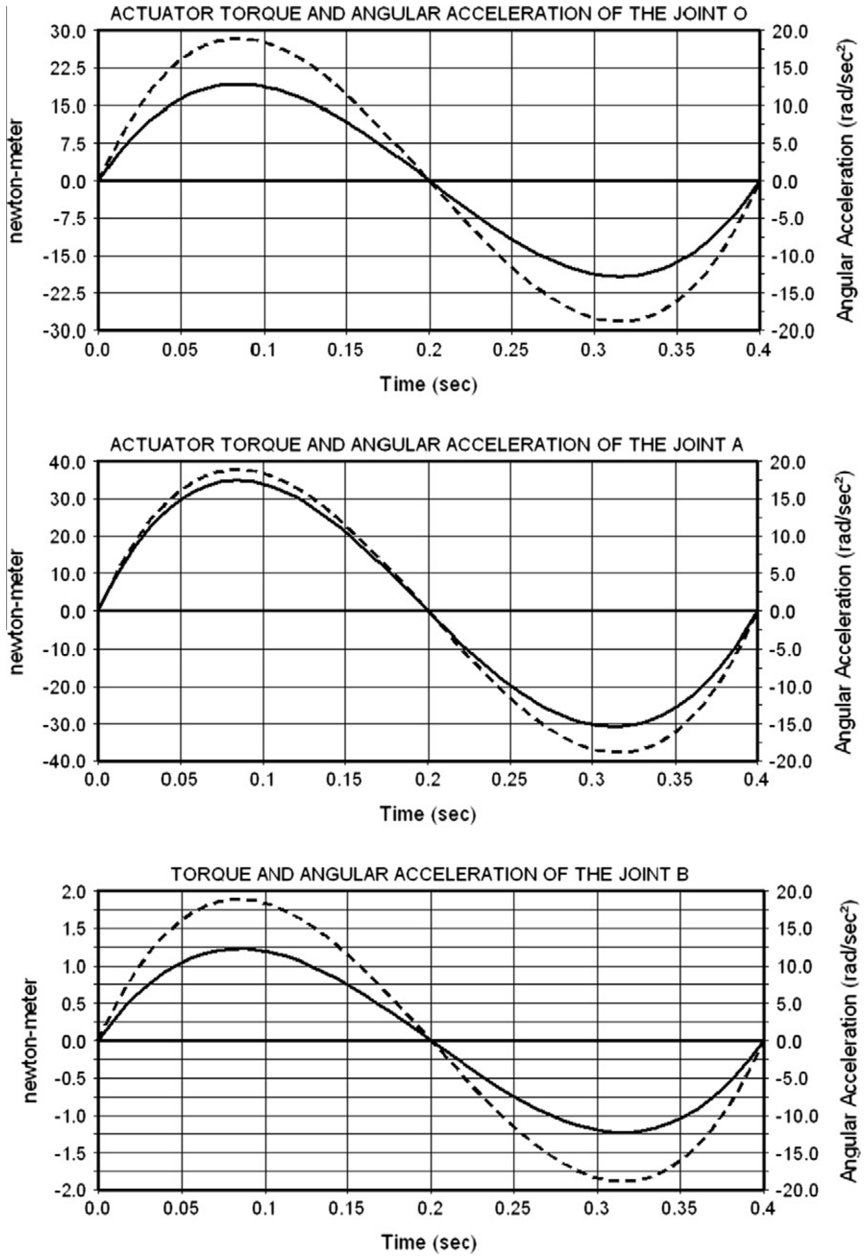

Fig. 5. Actuator torques (solid line) and angular accelerations (dashed line) for decoupled 3-DOF serial manipulator.

θ_{1F} = 0.5236; θ_{1F} = 0.5236; θ_{2I} = 1.0472; θ_{2F} = 1.5708, θ_{3I} = 0; θ_{3F} = 0.5236, are carried out by the following fifth order polynomial laws: $\theta_j = 5.2360t^3 - 7.8540t^4 + 3.1416t^5$ (j = 1, 2, 3), $0 \leqslant t \leqslant 0.4$ s.

As shown in Fig. 5 the dynamic equations of the simulated manipulator are decoupled, i.e. $\tau_1 = p_1\ddot{\theta}_1$, $\tau_2 = p_2\ddot{\theta}_2$ and $\tau_3 = p_3\ddot{\theta}_3$.

4. Conclusion

In order to increase the accuracy of high-speed manipulators the nonlinear dynamic control algorithms have been developed. However, taking into account the permanent tendency to decrease the price of robotic systems, the price of implementation of a complete dynamic control in the case of high-speed and precise manipulation on the industrial practice is still high. In the case of the reproduction of the trajectory in the Cartesian space by large number of given points is a laboriousness task requiring relatively long time of computation. Therefore, in many cases, the reduction (or cancellation) of coupling and nonlinearity in the manipulators, is necessary. The known mechanical solution can only be reached by unavoidable increase to the total mass of the manipulator and as a result, the input torques.

This paper introduced the improved design concept for the linearization and decoupling of dynamic equations of serial manipulators. It is achieved by adding to the initial architecture of the manipulator the secondary gears having prescribed inertia parameters. The determination of the parameters of the added gears is based on eliminating coefficients of nonlinear terms in the manipulator's kinetic and potential energy equations. After such a redistribution of masses the actuator torque in each driven joint becomes a linear function of its angular acceleration. The proposed design concept permits the dynamic decoupling of the serial manipulators with a relatively small increase in the total mass of the moving links. It provides an improvement in the known design solutions, rendering them more suitable for practical applications.

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