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Challenges in Motion Control Systems

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Abstract— Motion control technology is allowing development applications beyond structured environment of industrial plant and is making its way into unstructured world inhabited by people. Real-world haptics interactions associated with accurate models is becoming important technology with potential for application in many different fields like surgery, teleoperation, cooperative work, microsystems, education etc. Such applications of motion control technology require shifting a focus to the models, control strategies and algorithms needed for systems to work, interact and cooperate with humans or other artifacts in unstructured environment. These developments are opening numerous challenging issues to be solved in order to develop practical and competent systems that support the human operator, are fault tolerant, safe, easy to use, capable of adaptation to long term changes in environment. In this paper a number of the emerging issues within motion control technology are discussed including but not limited to new algorithms that allow concurrent force/position control, control of new PZT actuators, HUiL, control in micromanipulation, functionally related systems.

Keywords : motion control, acceleration control, disturbance observer, functionally related systems, human-in-the-loop, IoT

1. Section

Motion control is an technology that makes possible advances in many fields like high-tech manufacturing systems, high precision, advanced automotive applications, robotics, mechatronics, haptics, biomechanical applications, medical and welfare applications to name some. In many of these applications motion control is enabling machines-artifacts to perform in unstructured environment inhabited by humans. This requires shifting a focus of the motion control system design to the models, control strategies and algorithms needed for systems to work, interact and cooperate with humans or other artifacts in unstructured environment.

Being one of the technology drivers in the high tech systems industry, the high precision motion systems is often defined "as systems where linear or rotary devices are providing a controlled motion of a load, where the freedom of motion is restricted by design."[(1)] This description is narrowing motion control technology to the single degree of freedom systems and their combination in such a way that control of each of them can be executed separately. Much wider definition of the motion control as "a direct control of a mechanical system consisting of one or plural mechanical part, where every part is governed by the Lagrange equations[(2)]" is much wider and encompasses large variety of the systems, but it still does not include systems in which human appears as a part of the control loop.

In the future machines will be required to support human activity physically, while executing work on the distance from operator. Similarly manufacturing processes will need very high adaptability to fulfill a shift away from mass production. That would require machines to have much more sophisticated interaction with operator - interaction that in many instances would require transmission of the interaction force - real-world haptic sensing - to the operator[(3),(4)]. In the robotics field the development of humanoid, collaborative and service robots in general which are designed to work alongside human workers assisting them with a variety of tasks is taking place. The medical applications, especially robots supported surgery[(5)] is posing even stringent requirement on the motion safety and adaptability to the changes in environment.

The possibility record and then play back the haptic information would substantially change a way of the training people for executing tasks in which hatics information is important[(6)]. These and other applications require motion control algorithms to maintain safety and controlled interaction with humans and environment. The concurrent force/position control is one of the technologies that enables these developments[(7)].

In many systems the interaction with humans and human operator's role is essential to the correct working of the system[(8),(9)]. The design of the human-machine interactions in complex human-in-the-loop and cyber-physical-systems[(10)] is becoming very important. At present, there is no systematic methodology to synthesize human-in-the-loop[(11),(12)] control systems from high-level specifications, and it seems that the state of the art in system modeling techniques and feedback control strategies need to be advanced to address challenges posed by human-in-the-loop systems. Understanding and maximizing the collaboration between the control system and the human operator, and adopting a systematic design approach is crucial for optimum system performance.

Electromagnetic devices dominate the drive mechanisms in many applications including medical equipment. However, increasing accuracy requirements in the micron and nanometer ranges, along with an inclination toward miniaturization, dynamics streamlining, and interference immunity are pushing the physical limitations of electromagnetic drive systems. Piezoelectric (PZT) motors are providing viable implementation alternatives for a growing number of applications[(13)] especially in medical applications (MRI compatible devices[(14)], microdose dispensing, cell penetration and cell imaging in cytopathology,

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drug delivery devices, 3D scanning)[15] optics, measurement etc. because of inherent advantages for equipment design.

The growth of the area of application are opening numerous challenging issues to be solved in order to develop practical and competent motion control systems that ensures high precision, support human operator, are fault tolerant, safe, easy to use, capable of adaptation to long term changes. These and some other emerging issues within motion control technology or which may be changing the motion control technology landscape are discussed in this paper. The selection of the issues is obviously personal choice and many may or may not agree with it.

The paper is organized as follows. The design of the motion control in acceleration control framework is discussed in section 2. The solutions for SISO and MIMO motion control problems are shown. The control of functionally related but physically separated systems is discussed along with problems of the hierarchy of the tasks and the constraints task relationship. In the section 3. some current challenging areas of motion control application are discussed. These include the concurrent position-force control, real-world haptics, human-in-the-loop, cyber-physical-systems and new actuators based on the control of multitude of the functionally related PZT bimorphs.

2. System Description and Control

Configurations space description of a fully actuated mechanical system, or collection of k fully actuated system that together have n - degrees of freedoms, can be described by a set of nonlinear differential equations[7]

$$\begin{aligned} &\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \mathbf{\Phi}^T\boldsymbol{\lambda} = \boldsymbol{\tau} \\ &\mathbf{y} = \mathbf{y}(\mathbf{q}) \end{aligned} \tag{1}$$

In (1) $\mathbf{q} \in \Re^{n\times 1}$ denotes the configuration vector, assumed to belong to a bounded domain D^q; $\mathbf{A}(\mathbf{q}) \in \Re^{n\times n}$ stands for positive definite kinetic energy matrix with bounded strictly positive elements $0 < a_{ij}^- \le a_{ij}(\mathbf{q}) \le a_{ij}^+$ hence $A^- \le \|\mathbf{A}(\mathbf{q})\| \le A^+$, where A^-, A^+ are two known scalars with bounds $0 < A^- \le A^+$; $\mathbf{b}(\mathbf{q},\dot{\mathbf{q}}) \in \Re^{n\times 1}$ stands for vector Coriolis forces, viscous friction and centripetal forces and is bounded by $\|\mathbf{b}(\mathbf{q},\dot{\mathbf{q}})\| \le b^+$; $\mathbf{g}(\mathbf{q}) \in \Re^{n\times 1}$ stands for vector of gravity terms bounded by $\|\mathbf{g}(\mathbf{q})\| \le g^+$; $\boldsymbol{\tau} \in \Re^{nx1}$ stands for vector of generalized joint forces bounded by $\|\boldsymbol{\tau}\| \le \tau^+$, $\mathbf{y} = \mathbf{y}(\mathbf{q}) \in \Re^{m\times 1}$ stands for the output or, in robotics technology, a task, $\mathbf{\Phi}^T\boldsymbol{\lambda}$ stands for the configuration space projection of the operations space or constraint interaction force, with $\|\mathbf{\Phi}^T\boldsymbol{\lambda}\| \le \vartheta^+$ where elements of both matrix (operational space of constraint Jacobian) $\mathbf{\Phi}$ and vector $\boldsymbol{\lambda}$ are assumed bounded. Positive scalars A^-, A^+, b^+, τ^+, ϑ^+ are assumed known where any induced matrix or vector norm may be used in their definition. The $\mathbf{A}^{-1}(\mathbf{q}) \in \Re^{n\times n}$ can be interpreted as the control distribution matrix. The dependence of system parameters on the current systems configuration leads to an uncertainly. The matrix $\mathbf{A}(\mathbf{q}) > 0$, $\forall \mathbf{q} \in D^q$ allows that (1) could be rearranged into

$$\begin{aligned} &\ddot{\mathbf{q}} = \boldsymbol{\tau}_{\ddot{q}}(\boldsymbol{\tau},\mathbf{q}) - \boldsymbol{\tau}_{\ddot{q}}^{dis}; \\ &\mathbf{y} = \mathbf{y}(\mathbf{q}) \\ &\boldsymbol{\tau}_q^{dis} = \mathbf{b} + \mathbf{g} \\ &\boldsymbol{\tau}_{\ddot{q}} = \mathbf{A}^{-1}\boldsymbol{\tau}(\boldsymbol{\tau},\mathbf{q}); \boldsymbol{\tau}_{\ddot{q}}^{dis} = \mathbf{A}^{-1}\boldsymbol{\tau}_q^{dis} \end{aligned} \tag{2}$$

The systems (1) and (2) are nonlinear but affine in control. In some cases the part of the $\mathbf{A}(\mathbf{q})$ uncertainty could be included in disturbance. Then expressing $\mathbf{A}(\mathbf{q}) = \mathbf{A}_n(\mathbf{q}) + \Delta\mathbf{A}(\mathbf{q})$, with $\mathbf{A}_n(\mathbf{q}) > 0, \forall \mathbf{q} \in D^q$ (1) could be rearranged into the same form as shown in (2) with $\boldsymbol{\tau}_{\ddot{q}}(\boldsymbol{\tau},\mathbf{q}) = \mathbf{A}_n^{-1}\boldsymbol{\tau}$. In this case the coupling exists not only due to the forces $(\mathbf{b}+\mathbf{g})$ but also due to the uncertainties in the control distribution matrix and the term $\boldsymbol{\tau}_{\ddot{q}}^{dis} = \mathbf{A}_n^{-1}(\Delta\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g})$ stands for the bounded matched generalized disturbance consisting not only of the coupling and projection of external forces but also on the parameter variation with $\|\boldsymbol{\tau}_{\ddot{q}}^{dis}\| \le \tau^{+dis}$. In the further text (2) will be treated as a general expression allowing to handle, under certain conditions both cases.

The (2) can be effectively represented by n second order systems[7],

$$\begin{aligned} &\dot{q}_i = v_i, \\ &\ddot{q}_i = \dot{v}_i = \tau_{\ddot{q}}^i(\boldsymbol{\tau},\mathbf{q}) - \tau_{\ddot{q}}^{idis}; i = 1,...,n \\ &y_i = y_i(\mathbf{q}) \end{aligned} \tag{3}$$

Both $\tau_{\ddot{q}}^i$ and $\tau_{\ddot{q}}^{idis}$ are bounded by assumption. The output of the system $\mathbf{y} = \mathbf{y}(\mathbf{q})$ may be linear or nonlinear function of configuration space coordinates and in general it may depend on position and velocity. Here we will be assuming the dependence on position but treatment of the systems with $\mathbf{y} = \mathbf{y}(\mathbf{q},\dot{\mathbf{q}})$ can be easily derived. If (1)-(3) describes a set of physically separated systems (like for example mobile robots) then $\mathbf{y} = \mathbf{y}(\mathbf{q})$ stands for functional relationship between these systems[16].

2.1. Acceleration Control

The design problem consists in finding the best controller such that the performance is within specification for all prescribed situations (disturbances and system variations). The formulations (2) and (3) suggest a possibility to enforce desired configuration space acceleration in the system. For example for 1 dof system, under assumption that $(v_i, \tau_{\ddot{q}}^i)$ are measured and that disturbance can be modeled by $\dot{\hat{\tau}}_{\ddot{q}}^{idis} = 0$, from (3) and $\dot{\hat{\tau}}_{\ddot{q}}^{idis} = 0$ generalized disturbance $\tau_{\ddot{q}}^{idis}$ can be estimated by the dynamic system $\dot{z}_i = l_i(\tau_{\ddot{q}}^i - z_i + l_i v_i)$, $\hat{\tau}_{\ddot{q}}^{idis} = z_i - l_i v_i$, $l_i > 0$. and may be expressed in the form $\dot{\hat{\tau}}_{\ddot{q}}^{idis} + l_i\hat{\tau}_{\ddot{q}}^{idis} = l_i\tau_{\ddot{q}}^{idis}$. Note that in this design only design parameter is $l_i > 0$, an no parameters of the plant are involved. Further in the text in order to shorten expressions, we will use notation $\hat{\tau}_{\ddot{q}}^{idis} = Q_{qi}\tau_{\ddot{q}}^{idis}$, where Q_{qi} stands for a filter[17]. Applying the same design for all degrees of freedom the generalized disturbance vector $\hat{\boldsymbol{\tau}}_{\ddot{q}}^{dis} = [\hat{\tau}_{\ddot{q}}^{1dis} \ \ldots \ \hat{\tau}_{\ddot{q}}^{ndis}]^T$ could be estimated as well. The usage of the higher order disturbance model is beyond the scope of this text, because the general development remains the same. By expressing the control input as $\boldsymbol{\tau}_{\ddot{q}} = \ddot{\mathbf{q}}^{des} + \hat{\boldsymbol{\tau}}_{\ddot{q}}^{dis}$, where $\hat{\boldsymbol{\tau}}_{\ddot{q}}^{dis} = \mathbf{Q}_q\boldsymbol{\tau}_{\ddot{q}}^{dis}$ stands for generalized disturbance vector, and $\ddot{\mathbf{q}}^{des}$ stand for desired acceleration, the dynamics (2) reduces to

$$\begin{aligned} &\dot{\mathbf{q}} = \mathbf{v}, \\ &\ddot{\mathbf{q}} = \dot{\mathbf{v}} = \ddot{\mathbf{q}}^{des} - (\boldsymbol{\tau}_{\ddot{q}}^{dis} - \hat{\boldsymbol{\tau}}_{\ddot{q}}^{dis}) = \ddot{\mathbf{q}}^{des} - \boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}_{\ddot{q}}^{dis}) \\ &\boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}_{\ddot{q}}^{dis}) = (\mathbf{I} - \mathbf{Q}_q)\boldsymbol{\tau}_{\ddot{q}}^{dis} \end{aligned} \tag{4}$$

Design of the filter $\mathbf{Q}_q$ may enforce $\boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}_{\ddot{q}}^{dis}) \approx \mathbf{0}$. In the systems with stringent requirements the structure and dynamics of the estimation error has to be carefully evaluated in order to avoid undesired uncompensated dynamics.

Selection of desired acceleration under assumption that $\boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}_{\ddot{q}}^{dis}) \approx \mathbf{0}$ is straight forward. By selecting $\ddot{\mathbf{q}}^{des} = \ddot{\mathbf{q}}^{ref} - \mathbf{K}_D(\dot{\mathbf{q}}^{ref} - \dot{\mathbf{q}}) - \mathbf{K}_P(\mathbf{q}^{ref} - \mathbf{q})$ with $\mathbf{K}_D, \mathbf{K}_P > 0$ the tracking of the reference $\mathbf{q}^{ref}$ will be guaranteed and closed loop dynamics will be determined by $\mathbf{K}_D, \mathbf{K}_P > 0$. Strictly speaking the closed loop dynamics will be determined by $\left(\ddot{\mathbf{q}}^{ref}-\ddot{\mathbf{q}}\right)+\mathbf{K}_D\left(\dot{\mathbf{q}}^{ref}-\dot{\mathbf{q}}\right)+\mathbf{K}_P\left(\mathbf{q}^{ref}-\mathbf{q}\right)=\boldsymbol{\varepsilon}_q\left(\mathbf{Q}_q,\boldsymbol{\tau}_{\ddot{q}}^{dis}\right)$, thus the importance of the correct disturbance estimation. We will discuss this in more details in section 2.3.

2.2. Output Control In the second step one has to find control input enforcing output control and desired closed loop system behavior. Here $\mathbf{y}(\mathbf{q})$ is denoted as a control output without discussing its physical nature. As we will see later in section 3, $\mathbf{y}(\mathbf{q})$ could be a description of task, or a constraint, or for example force in contact with predominantly spring like environment, or the functional relationship between system or multiple systems coordinates that needs to be maintained. For known output reference $\mathbf{y}^{ref}(t)$ the dynamics of the output error $\mathbf{x}(\mathbf{q},t)=\mathbf{y}(\mathbf{q})-\mathbf{y}^{ref}(t)$ becomes

$$\begin{aligned}&\ddot{\mathbf{x}}=\mathbf{J}\ddot{\mathbf{q}}^{des}-\mathbf{f}_{\ddot{x}}^{dis}=\mathbf{f}_{\ddot{x}}^{com}-\mathbf{f}_{\ddot{x}}^{dis};\mathbf{J}=\left\lfloor\frac{\partial\mathbf{y}}{\partial\mathbf{q}}\right\rfloor\in\Re^{m\times n}\\&\mathbf{f}_{\ddot{x}}^{com}=\mathbf{J}\ddot{\mathbf{q}}^{des}\\&\mathbf{f}_{\ddot{x}}^{dis}=-\left(\dot{\mathbf{J}}\dot{\mathbf{q}}-\mathbf{J}\boldsymbol{\varepsilon}\left(\mathbf{Q},\boldsymbol{\tau}_{\ddot{q}}^{dis}\right)-\ddot{\mathbf{y}}^{ref}(t)\right)\end{aligned}\tag{5}$$

where $\mathbf{J}\in\Re^{m\times n}$ is a Jacobian assumed to be a full row rank matrix. Note that components of the operational space generalized disturbance $\mathbf{f}_{\ddot{x}}^{dis}$ can be estimated the same way as the configuration space generalized disturbance $\boldsymbol{\tau}_{\ddot{q}}^{dis}$ (by assuming $\hat{f}_{\ddot{x}}^{idis}=0$ *i*-th component can be estimate, under assumption that pair the dynamic system $\left(f_{\ddot{x}}^{i},\dot{x}_i\right)$ is measured, by a simple dynamical system the $\dot{z}_i=l_i\left(f_{\ddot{x}}^{i}-z_i+l_i\dot{x}_i\right)$, $\hat{f}_{\ddot{x}}^{idis}=z_i-l_i\dot{x}_i$, $l_i>0$ and may be expressed in the form $\dot{\hat{f}}_{\ddot{x}}^{idis}+l_i\hat{f}_{\ddot{x}}^{idis}=l_i f_{\ddot{x}}^{idis}$). Similarly as in the configuration space acceleration control the disturbance vector can be expressed as $\hat{\mathbf{f}}_{\ddot{x}}^{dis}=\mathbf{Q}_f\mathbf{f}_{\ddot{x}}^{dis}$, where $\mathbf{Q}_f$ stands for a filter. The estimated disturbance converges to $\mathbf{f}_{\ddot{x}}^{dis}$. By expressing $\mathbf{f}_{\ddot{x}}^{com}=\ddot{\mathbf{x}}^{des}+\hat{\mathbf{f}}_{\ddot{x}}^{dis}$, where, and $\ddot{\mathbf{x}}^{des}$ stands for desired error acceleration, yields

$$\begin{aligned}&\ddot{\mathbf{x}}=\ddot{\mathbf{x}}^{des}-\left(\mathbf{I}-\mathbf{Q}_f\right)\mathbf{f}_{\ddot{x}}^{dis}=\ddot{\mathbf{x}}^{des}-\boldsymbol{\varepsilon}_f\left(\mathbf{Q}_f,\mathbf{f}_{\ddot{x}}^{dis}\right)\\&\boldsymbol{\varepsilon}_f\left(\mathbf{Q}_f,\mathbf{f}_{\ddot{x}}^{dis}\right)=\left(\mathbf{I}-\mathbf{Q}_f\right)\mathbf{f}_{\ddot{x}}^{dis}\end{aligned}\tag{6}$$

For $\boldsymbol{\varepsilon}_f\left(\mathbf{Q}_f,\mathbf{f}_{\ddot{x}}^{dis}\right)\approx\mathbf{0}$ the selected control input enforces desired output error acceleration $\ddot{\mathbf{x}}=\ddot{\mathbf{x}}^{des}\Rightarrow\ddot{\mathbf{y}}=\ddot{\mathbf{y}}^{ref}+\ddot{\mathbf{x}}^{des}$. For example, by selecting $\ddot{\mathbf{x}}^{des}=-\mathbf{K}_D\dot{\mathbf{x}}-\mathbf{K}_P\mathbf{x}$; $\mathbf{K}_D,\mathbf{K}_P>0$ the output error dynamics is stable and governed by second order equation $\ddot{\mathbf{x}}+\mathbf{K}_D\dot{\mathbf{x}}+\mathbf{K}_P\mathbf{x}=\boldsymbol{\varepsilon}_f\left(\mathbf{Q}_f,\mathbf{f}_{\ddot{x}}^{dis}\right)\approx\mathbf{0}$. From $\mathbf{f}_{\ddot{x}}^{com}=\mathbf{J}\ddot{\mathbf{q}}^{des}$ the desired configuration space acceleration can be determined as $\ddot{\mathbf{q}}^{des}=\mathbf{J}^{\#}\mathbf{f}_{\ddot{x}}^{com}$ or $\ddot{\mathbf{q}}^{des}=\mathbf{J}^{\#}\left(\ddot{\mathbf{x}}^{des}+\hat{\mathbf{f}}_{\ddot{x}}^{dis}\right)$, where $\mathbf{J}^{\#}\in\Re^{n\times m}$ is the right generalized pseudoinverse in the form $\mathbf{J}^{\#}=\mathbf{W}^{-1}\mathbf{J}^T\left(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^T\right)^{-1}\mathbf{J}$. Selection of $\mathbf{W}$ can be regarded as a design parameter. By selecting $\mathbf{W}=\mathbf{A}$ the control is minimizing $0{,}5\dot{\mathbf{q}}^T\mathbf{A}\dot{\mathbf{q}}$ under constraints $\dot{\mathbf{x}}=\mathbf{J}\dot{\mathbf{q}}$. From the desired configuration space acceleration one can find the configuration space generalized forces as $\boldsymbol{\tau}=\mathbf{A}\left(\mathbf{J}^{\#}\left(\ddot{\mathbf{x}}^{des}+\hat{\mathbf{f}}_{\ddot{x}}^{dis}\right)+\hat{\boldsymbol{\tau}}_{\ddot{q}}^{dis}\right)$.

Essential part of the control design is the two step procedure:

(i) the configuration space acceleration control (inner loop) is performed first (as discussed in section 2.2,) and

(ii) the operational space acceleration control (outer loop) is designed in the second step.

This separation property enables two independent design stages: one for the generalized disturbance rejection - effectively acceleration control. In this stage design of the generalized disturbance observer with small estimation error is a dominant design issue.

In the second stage a controller is designed to assure desired closed loop performance. In this stage the imperfections resulting from the dynamic error in the generalized disturbance estimation could be taken into account.

2.3. Disturbance Observer[17-24] The key idea of a generalized disturbance observer is a possibility to design an autonomous dynamical system that generates the disturbances.[18] In the frequency range for which estimation errors are small the generalized disturbance feed makes the real plant behave like the nominal plant model. Imperfection of the disturbance estimation will lead to the discrepancies of the ideal and achievable system. In order to understand the issues related to the generalized disturbance design let us look at SISO plant. The SISO plant $a^{-1}P$ with disturbance feedback $\hat{\tau}^{dis}=Q\tau^{dis}$ and nominal plant model assumed as $a_n^{-1}P_n$, can be in frequency domain represented as[7]

$$q=P_n\frac{1}{a_na^{-1}P^{-1}P_n(1-Q)+Q}\ddot{q}^{des}-P\frac{a_na^{-1}P^{-1}P_n(1-Q)}{a_na^{-1}P^{-1}P_n(1-Q)+Q}\tau_{\ddot{q}}^{dis}\tag{7}$$

The dynamics in the control loop and in the disturbance loop look quite complex. For selected nominal plant $a_n^{-1}P_n$, the filter Q appears as a design parameter and should satisfy certain constraints[20]:

(a) *Relative degree*—In order to enable practical implementation of the disturbance observer, filter should have a relative degree larger than or equal to the relative degree of the nominal plant model.

(b) *Global shape*—As disturbances should be rejected as much as possible, from (7) follows that Q should be unity, but the requirement on the relative degree contradicts this. The compromise is in selecting $Q\approx1$ within the frequency range in which disturbance is predominant.

(c) Model misfit - Q being designed as a low-pass filter at low frequencies $Q\approx1$ and (7) reduces to $q=P_n\ddot{q}^{des}-0\times P\tau_{\ddot{q}}^{dis}$, thus we have a nominal plant as expected. At high frequencies $Q\approx0$ and (7) reduces to $q=(aP/a_n)\ddot{q}^{des}-P\tau_{\ddot{q}}^{dis}$.

Despite the fact that Q should adhere to above basic requirements, there is still a fair amount of freedom in its selection. This freedom can be used to include a specific disturbance model in the observer design. For a specific choice of filter with relative degree *p*, the disturbance observer implements *p*-integrating actions in the acceleration control loop[2,7,20]. If the nominal and real plant are the same then the same structure can be used for the external force estimation[3-7]

The generalized disturbance observer has two inputs ($q_i,\tau_{\ddot{q}}^{i}$) thus in can be designed as $z=\hat{\tau}_{\ddot{q}}^{dis}=W_1\tau_{\ddot{q}}-W_2q$, where W_1,W_2 are proper transfer functions to be selected during the design. In this case the system dynamics with generalized disturbance feed can be expressed as[7]

$$\begin{aligned}&q=P_n\frac{P_n^{-1}}{aa_n^{-1}P^{-1}(1-W_1)+W_2}\ddot{q}^{des}-P\frac{P^{-1}(1-W_1)}{aa_n^{-1}P^{-1}(1-W_1)+W_2}\tau_{\ddot{q}}^{dis}\\&q=P_nQ_q^{con}\ddot{q}^{des}-PQ_q^{dis}\tau_{\ddot{q}}^{dis}\end{aligned}\tag{8}$$

In (8) W_1,W_2 can be selected to ensure desired dynamic influence of the generalized disturbance represented by Q_q^{dis}. Then the modification of the nominal plant Q_q^{con} due to the design error in the generalized disturbance estimation can be determined and taken into consideration in the output controller design.

Similar results may be obtained if the nominal plant tracking control is used for disturbance estimation.

The same approach can be used to estimate some other function of the system state[7,19,21]. For example, by selecting the ideal observer output as $z = W_N q$ with W_N known proper or not proper transfer function, real observer output as $\hat{z} = W_1 \tau_{\ddot{q}} + W_2 q$, with W_1, W_2 as proper transfer functions and estimation error $\varepsilon_z = z - \hat{z} = W_d \tau_q^{dis}$ one can determine conditions for calculating W_1, W_2 as $a^{-1}P(W_N - W_2) - W_1 = 0$ and $a^{-1}P(W_N - W_2) - W_d = 0$.

Getting right disturbance compensation is one of the central issues in the motion control system design especially for the high accuracy applications (like high-tech manufacturing tools, semiconductor industry, micro systems application, medical application ..). There are some issues that still need careful attention in disturbance observer design:

Most of the design procedures are developed for so called matched disturbances, which are common in motion control systems. The coherent design procedure for unmatched disturbance is yet to be developed[21].

In most of the cases disturbance observer is designed in the continuous time and then implemented in the discrete time. This may not be best solution, so the discrete-time design of the disturbance observer need to be examined in more details[23].

The disturbance observer parametrization allows selection of the closed loop dependence on unknown input as a design parameter for selection of the disturbance observer filter[7].

Selection of the plant and the nominal models is critical due to complex dynamics of the loop with estimated disturbance feed. The problem is even more complex in the case of the actuator supply with power stages that work in discontinuous mode, or nonlinear characteristics of actuators (like PZT with hysteresis). In most of the cases these nonlinearities may not be so easy incorporated in the nominal plant model. Large difference between plant and nominal model may lead to the instability. The dynamics of the generalized torque controller is not treated here, but high precision systems that may be required[7] .

Structure of the plant with disturbance observer (7) points out to a need of observer-controller co-design in order to reach required performance. This is especially true in the high-tech manufacturing system and the medical applications. The co-design may assure desired performance in the wider frequency range and better noise rejection in the high frequency region[25].

3. Control of Functionally Related Systems

The idea of functionally related systems had been proposed in[26,27,7] where system operation requirements had been defined in so called common and differential mode[26-32]. In[7,17] the idea of functionally related systems had been further expanded to include relationship defined by a linear or nonlinear function of the configuration space coordinates or system outputs. Both approaches can be applied to situations in which, otherwise physically separated systems, are being required to maintain relationship that may be described by a function(s) of the system coordinates or their outputs. It has been argued that this allows simpler and more natural way of the system operation (task) description (for example bilateral control, aggregation of mobile systems ...).

Natural requirement for such systems is that the functional constraints should specify a realizable state of the system. The obtained realizable state may or may not be unique depending on the redundancy of the functional relationship with respect to the dimension of the configuration space and of the form of the functional constraints. For given system's total number of degrees of freedom, a certain number of these functions can be executed simultaneously. A set of the functions that is being executed in a particular moment defines current task.

Let have a $n-$dof fully actuated mechanical system. It could be just a single multi body system or a collection of m systems that combined have $n-$dof. Let desired operation of the system is described by a set of vector valued functions $\mathbf{y}_i(\mathbf{q}) \in \Re^{k_i \times 1}$, $i = 1,..., m$ each required to track its reference $\mathbf{y}_i^{ref}(\mathbf{q}) \in \Re^{k_i \times 1}$. Let also the set of functions satisfy condition that $\sum_{i=1}^{m} k_i = n$, all $\mathbf{y}_i(q)$ are two times differentiable and Jacobians $\partial \mathbf{y}_i(\mathbf{q}) / \partial \mathbf{q} = \mathbf{J}_{yi}$ have full row rank. In section 2 we sketched design of the control for output $\mathbf{x}_i = \mathbf{y}_i - \mathbf{y}_i^{ref}$ but did not discuss details. Let the output vector $\mathbf{y} = [\mathbf{y}_1 \ \ ... \ \ \mathbf{y}_m]^T$ is required to tracks its reference $\mathbf{y}^{ref}$. In addition we may require that control of functions $\mathbf{y}_i$ is dynamically decoupled from each other.

3.1 Redundant Task Control The closed loop dynamics for single task $\mathbf{x}_i$ with the control input $\mathbf{f}_{\ddot{x}i}^{com} = \ddot{\mathbf{x}}_i^{des} + \hat{\mathbf{f}}_{\ddot{x}i}^{dis}$ becomes

$$\ddot{\mathbf{x}}_i = \ddot{\mathbf{x}}_1^{des} + \boldsymbol{\varepsilon}_f\left(\mathbf{f}_{\ddot{x}i}^{dis}\right) \tag{9}$$

The desired configuration space acceleration becomes

$$\ddot{\mathbf{q}}^{des} = \mathbf{J}_i^{\#}\left(\ddot{\mathbf{x}}_i^{des} - \dot{\mathbf{J}}_i \dot{\mathbf{q}} + \mathbf{J}_i \boldsymbol{\varepsilon}_q\left(\boldsymbol{\tau}_{\ddot{q}}^{dis}\right)\right) - \boldsymbol{\varepsilon}_f\left(\mathbf{f}_{\ddot{x}}^{dis}\right) + \left(\mathbf{I} - \mathbf{J}_i^{\#}\mathbf{J}_i\right)\ddot{\mathbf{q}}_0 \tag{10}$$

Where $\ddot{\mathbf{q}}_0 \in \Re^{n \times 1}$ is arbitrary acceleration in configuration space. By plugging (11) into (4) the overall system dynamics can be expressed as

$$\begin{aligned} &\left(\mathbf{I} - \mathbf{J}_i^{\#}\mathbf{J}_i\right)\ddot{\mathbf{q}} = \left(\mathbf{I} - \mathbf{J}_i^{\#}\mathbf{J}_i\right)\ddot{\mathbf{q}}_0 + \mathbf{J}_i^{\#}\mathbf{J}_i \boldsymbol{\varepsilon}_q\left(\boldsymbol{\tau}_{\ddot{q}}^{dis}\right) \\ &\ddot{\mathbf{x}}_i = \ddot{\mathbf{x}}_1^{des} + \boldsymbol{\varepsilon}_f\left(\mathbf{f}_{\ddot{x}i}^{dis}\right) \end{aligned} \tag{11}$$

From (11) follows in addition to the redundant task at the same time additional tasks such that $\sum_{j=1}^{m-1} k_j = n - k_i$ could be executed.

3.2. Concurrent Multi-Task Control The dynamics of the task error $\mathbf{x} = \left(\mathbf{y} - \mathbf{y}^{ref}\right) \in \Re^{n \times 1}$ can be, by taking into account (5), written as

$$\begin{aligned} &\ddot{\mathbf{x}} = \mathbf{J}\ddot{\mathbf{q}}^{des} - \mathbf{f}_{\ddot{x}}^{dis} = \mathbf{f}_{\ddot{x}}^{com} - \mathbf{f}_{\ddot{x}}^{dis}; \mathbf{J}_i = \frac{\partial \mathbf{x}_i}{\partial \mathbf{q}}, i = 1,..., m \\ &\mathbf{f}_{\ddot{x}}^{com} = \begin{bmatrix} \mathbf{f}_{\ddot{x}1}^{com} \\ .... \\ \mathbf{f}_{\ddot{x}m}^{com} \end{bmatrix}; \mathbf{f}_{\ddot{x}}^{dis} = \begin{bmatrix} \mathbf{f}_{\ddot{x}1}^{dis} \\ .... \\ \mathbf{f}_{\ddot{x}m}^{dis} \end{bmatrix}; \mathbf{J} = \begin{bmatrix} \mathbf{J}_1 \\ .... \\ \mathbf{J}_m \end{bmatrix} \in \Re^{n \times n}; \end{aligned} \tag{12}$$

By assumption Jacobian $\mathbf{J}$ is full rank matrix, thus the desired configuration space acceleration can be expressed $\ddot{\mathbf{q}}^{des} = \mathbf{J}^{-1}\mathbf{f}_{\ddot{x}}^{com}$. The possibility to dynamically decouple the functions would lead to simplified design. At the same time the operational constraints may require that certain hierarchy among functions is established. The simplest example of the is relationship between task and constraints - task could be executed only if constraints are not violated. The hierarchical priority requirements leads the selection

$$\mathbf{J} = \begin{bmatrix} \mathbf{J}_1 \\ \boldsymbol{\Omega}_2(\mathbf{J}_2) \\ .... \\ \Omega_m(\mathbf{J}_m) \end{bmatrix}; \ddot{\mathbf{q}}^{des} = \begin{bmatrix} \mathbf{J}_1^{\#} & \boldsymbol{\Omega}_2^{\#} & ... & \boldsymbol{\Omega}_m^{\#} \end{bmatrix} \begin{bmatrix} \mathbf{f}_{\ddot{x}1}^{com} \\ \mathbf{f}_{\ddot{x}2}^{com} \\ .... \\ \mathbf{f}_{\ddot{x}m}^{com} \end{bmatrix} \tag{13}$$

Where $(\bullet)_k^{\#}$ are generalized weighted pseudoinverse matrices associated with *k-th* output. Selection $\mathbf{\Omega}_i = \mathbf{J}_i \mathbf{N}_{J_1,\dots,J_{i-1}}$, $\mathbf{N}_{J_1,\dots,J_{i-1}} = \left(\mathbf{I} - \mathbf{J}_1^{\#}\mathbf{J}_1 - \dots - \mathbf{J}_{i-1}^{\#}\mathbf{J}_{i-1}\right)$ leads to dynamical decoupling of tasks and allows fulfilling the priority requirements(7,17,33,34). Proposed control, with some modifications due to implementation peculiarities, has been used for cooperation control of articulated and mobile robots(27). In(17) functionally related systems control had been applied to design bilateral control, cooperative work of articulate robots, formation control of mobile robots, control of PZT motors.

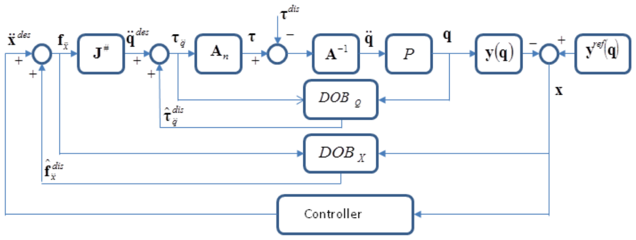

Fig. 1 Structure of the Acceleration Control based task control system

This approach leads to relatively simple solution but there are some issues that need to be addressed in order to make full understanding of its potential. These issues are related to the task specification in the case when $\mathbf{x}(\mathbf{q},t)$ is nonlinear and may have multiple solutions. Finding a method how to restrict selection is still an open issue. The (13) opens an opportunity for the dynamical changed of the subtasks. The general rule requires - matrix $\mathbf{J}$ should have full column rank - thus if during execution one subtask should be changed by another the new matrix should have full column rank. The structure of the control system is depicted in Fig. 1

4. Some Applications of Motion Control

4.1. Concurrent Position Tracking and Force Control In the future, machines will be more and more interacting with humans or be required to transmit of haptic sense to the operator. That capability is seen as a key of next innovation in motion control systems with more sophisticated interaction with environment and/or with operator will include transmission of the interaction force - real-world haptic sensing - to the operator(35,36,37) or modification of motion due to interaction with environment. This would require incorporation of the force control within the machine controller and design input torques as function of position and force (or stiffness in some cases). The need to modify motion due to the interaction force is already a necessity for preserving safety of the machine operation in contact with humans. Here, as example of possible solution, the formulation presented in(7) is shown. For SISO system the position tracking can be realized if the output error $e_i = q_i^{ref} - q_i$ is forced to satisfy $\dot{e}_i + Ce_i = \sigma_i = 0$, $C > 0$. The generalized error σ may be interpreted as a force pulling system from its current position $q_i(t)$ to reference position $q_i^{ref}(t)$ with stiffness C. Interaction force with environment with environment in position $q_{ei}(t)$ can be expressed as $D_e\dot{e}_{ei} + Ke_{ei} = f_{ei}$, $e_{ei} = q_{ei} - q_i$. In contact point $q_{ei} \neq q_i^{ref}$ the "action-reaction" law must be satisfied thus $\sigma_i(q_i, q_i^{ref}) + f_{ei}(q_{ei}, q_i) = \sigma_{ei}(q_i, q_{ei}, q_i^{ref}) = 0$ must be maintained. Thus if instead of position generalized error the $\sigma_i(t) + \lambda f_{ei}(t) = \sigma_{ei}^*(q,f,t)$, $\lambda > 0$ is used in the control input design, then for $\sigma_{ei}^* = 0$ the force balance leads to $\sigma_i(q,t) = -\lambda f_{ei}(t)$ and by selecting λ (or making it function of the difference between desired and actual force, or function of stiffness) one can control the interaction force. Solution is simple, straight forward and can be applied if the model of the interaction force is different. The key idea is that if there is no interaction with environment position control is enforced and if interaction appears then force control or stiffness control (by changing λ) is maintained.

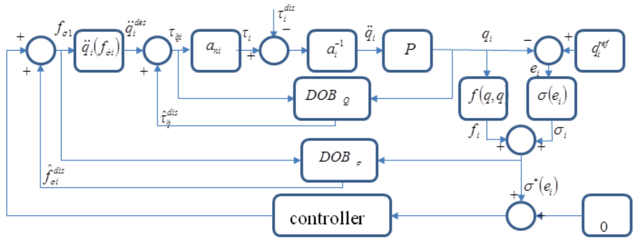

Fig. 2 Structure of the concurrent position - force control

The control can be easily determined. From $\dot{\sigma}_{ei}^*(q,f,t) = f_{\dot{\sigma}i}(\ddot{q}_i) - f_{\dot{\sigma}i}^{dis}$ and under assumption that $\hat{f}_{\dot{\sigma}i}^{dis} = 0$ the generalized disturbance can be estimated and selection $f_{\dot{\sigma}i}(\ddot{q}_i) = \hat{f}_{\dot{\sigma}i}^{dis} - k_\sigma \dot{\sigma}_{ei}^*(q,f,t)$ would ensure convergence to $\dot{\sigma}_{ei}^*(q,f,t) = 0$. The desired acceleration can be then derived from $f_{\dot{\sigma}i}(\ddot{q}_i)$. The structure of the system is shown in Fig.2. Note that there is no topological difference from system presented in Fig. 1, just a the control error is now defined differently.

4.2. Real-World Haptics(3-5,,35-37) When operator is required operating a system at a distant location than haptic information (interaction force) is transmitted to operator as an information needed to execute sensitive task. This arrangement is known as bilateral control. In such system the synchronization of position (position tracking) and artificial realization of law of action and reaction (force feedback) are required. These requirements may be formulated in the form of some functions of state of the two systems tracking their references. Such a formulation is the same as one we already discussed in the section 3. Having master side (in contact with operator) variable labeled by suffix m and slave side variable by suffix s the operational requirements of bilateral system will be realized if operational space errors are enforced to be zero.

$$\begin{aligned} x_m(q_m) - \alpha x_s(q_s) &= y_x(q_m, q_s) \underset{\substack{t\to\infty \\ t\geq t_0}}{\rightarrow} 0 \\ f_m(q_m) + \beta f_s(q_s) &= y_f(q_m, q_s) \underset{\substack{t\to\infty \\ t\geq t_0}}{\rightarrow} 0; \alpha, \beta > 0 \end{aligned} \tag{14}$$

This functional relationship ensures that position is tracking and the interaction force with environment is transferred to the operator side, thus ensuring concurrent position and force control. The scaling coefficients allows for the adaptation of the level of forces and motion if it is required to match operators capabilities with one exerted to the environment. It is interesting to observe that here we have functional relationship defined on system coordinates (positions) and on the functions of the system coordinates (forces). In order to show that previous results can be directly applied let us assuming SISO systems on the master and slave side. Then one can easily derive

$$\begin{aligned} \ddot{y}_x(q_m, q_s) &= \ddot{q}_m^{des} - \alpha \ddot{q}_s^{des} - \left(\varepsilon_m^{dis} - \alpha \varepsilon_s^{dis}\right) = f_{yx}^{des} - f_{yx}^{dis} \\ \ddot{y}_f(q_m, q_s) &= \ddot{q}_m^{des} + \beta \ddot{q}_s^{des} + \left(\varepsilon_m^{dis} + \beta \varepsilon_s^{dis} + f_{ms}^{dis}\right) = f_{yf}^{des} - f_{yf}^{dis} \end{aligned} \tag{15}$$

By selecting $f_{yx}^{des} = \hat{f}_{yx}^{dis} + \ddot{y}_x^{des}$ and $f_{yf}^{des} = \hat{f}_{yf}^{dis} + \ddot{y}_f^{des}$, where $\hat{f}_{yx}^{dis}$ and $\hat{f}_{yf}^{dis}$ are estimation of the generalized disturbances, the desired dynamics in position and force control can be obtained. The configuration space accelerations are $(\alpha+\beta)\ddot{q}_s^{des} = -f_{yx}^{des} + f_{yf}^{des} + \varepsilon_{yx}$ and $(\alpha+\beta)\ddot{q}_m^{des} = \beta f_{yx}^{des} + \alpha f_{yf}^{des} + \varepsilon_{yf}$, where ε_{yx} and ε_{yf} are the disturbance compensation errors in *position* and force channels respectively. The topology of the system is depicted in Fig.3. It should be noted here that (14) specifies only relative relationship, $x_m(q_m) = \alpha x_s(q_s)$ and $f_m(q_m) = -\beta f_s(q_s)$ while actual values of the position and force are determined by the operator or another external source.

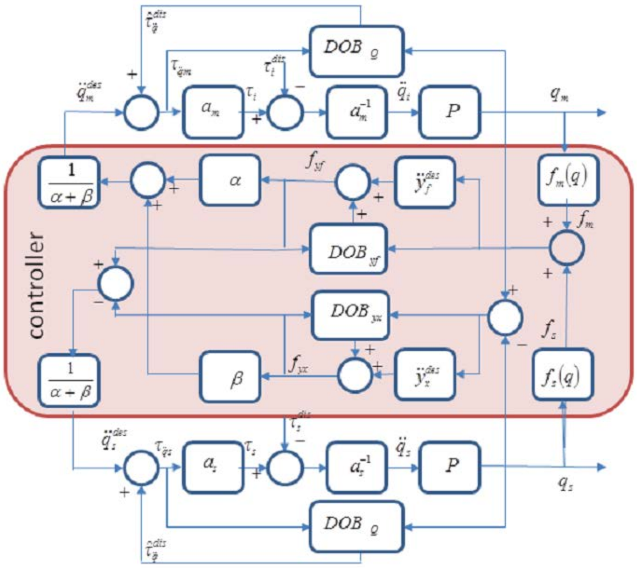

Fig. 3 Structure of bilateral control systems

Bilateral systems are one of the forms of the human-in-the-loop control systems. In its design the human operator is setting absolute value of both position and the interaction force thus it serves in a sense as a reference generator. In systems with communication delay having human-in-the-loop requires special attention due to the possibility to induce oscillations.

The communication over network in motion control system poses a challenge in maintaining desired system behavior in the environment susceptible for communication delay. The variable delay and the algorithms to cope with it are for a long time in focus of the control system community[7,38,42-44]. How to treat bilateral systems with variable delay is still open question for research.

4.3 Human-in-the-Loop Control The degree of control in a process is a function of the predictability of process behavior and the degree of its complexity. For all but the simplest of elements, it is not possible to model a plant fully or with sufficient explicitness. Nor is it possible to consider how external influences can affect the control system. Safety-critical technical systems interact with human being, and the human operator's role is essential to the correct working of the system[39,40]. Examples of such systems include fly-by-wire control systems, automobiles with driver assistance systems, medical devices...

The luck of completeness of the description of the system function or control implementation in software along with unpredictability of the components' error lead to operational conditions that may not be taken into account thus limiting the possibility to reflect all peculiarities of the system to their full extent. For example, in the absence of adequate assumptions constraining its behavior, the environment can be modeled as oversimplified or over complex, causing the autonomous controller to wrongly react at data received from environment. Additionally, the high-level specification might abstract away from inherent physical limitations of the system, such as insufficient range of sensors, which must be taken into account in any real implementation.

At present, there is no systematic methodology for synthesis of a combination of human and autonomous control from high-level specifications[10,41]. Major research challenges of systems involving human-in-the-loop control are: (i) understanding the complete spectrum of human-in-the-loop control and possibility to correctly specify operational criteria, (ii) modeling human behavior and incorporation of these models into the formal feedback control; (iii) formalization of human-in-the-loop control systems and the problem of synthesizing such controllers from high.

At this stage of development it seems that state of the art system modeling techniques and feedback control strategies need to be advanced to address these challenges. Understanding and maximizing the collaboration between the control system and the human operator, and adopting a systematic design approach is crucial for optimum system performance It is critical that the human operator remains in charge, the decision support system should not attempt to define what to do.

4.4. Cyber-Physical-Systems In the last few years the socalled "Cyber-Physical-Systems (CPS) which consists of the sensing and control of physical phenomena though network of interconnected devices that work together to achieve common goals[11]" is attracting attention. This concept of automatic monitoring and control of environments is already used by many applications. From industrial applications that monitor and actuate several factory processes and real-world haptic systems, to smart phone-based social networking applications that achieve metropolitan-wide reduction of pollution and traffic. Motion control systems, one of typical CPS applications, have been widely used in various industrial fields such as packaging, semiconductor manufacturing, and production machinery, and are becoming important driving components for the next industrial revolution. The CPS can encompass a multitude of domains. Of interest for motion control technology are CPSs which represent a convergence of complex "intelligent" machines, robots, actuators, sensor networks, mobile computing and the Internet-of-Things to achieve adaptable manufacturing and/or adaptable environment.

As mentioned the communication over network in motion control system poses a challenge. The questions like scheduling, network security, fault tolerance, etc., are emerging challenging problems along with communication constraints like bandwidth, random delay and packet loss, to computational constraints due to the large amount of data or to the distributed nature of the sensing and control, to real-time implementation on limited resources devices, and complexity due to the large number of possibly unreliable agents involved[45]

In these CPSs role will be changing but human will remain an essential part of the system. At the current stage of the development the humans are treated as an external element to the control loop. The further development of the autonomous systems will need to take into consideration human intents, psychological states, emotions and actions inferred through sensory data through human-in-the-loop controls.

4.5 New PZT Actuators Electromagnetic devices dominate the drive mechanisms in many applications including medical equipment. However, increasing accuracy requirements in the micron and nanometer ranges, along with an inclination toward miniaturization, dynamics streamlining, and interference immunity are pushing the physical limitations of electromagnetic drive systems. Piezoelectric (PZT) motors are providing viable implementation alternatives for a growing number of applications especially in medical applications (MRI compatible devices, microdose dispensing, cell penetration and cell imaging in cytopathology, drug delivery devices, 3D scanning) optics, measurement etc. because of inherent advantages for equipment design[46-50].

Special attention are attracting PZT motors which can provide unlimited motion and very high accuracy. Piezo stepper motors can achieve high forces of up to 700 N and picometer resolution. These motions can be conducted in the presence of strong magnetic fields or at very low temperatures. PZT stepper linear motors usually consist of several individual piezo actuators and generate motion through a succession of coordinated clamp/unclamp and expand/contract cycles. Each extension cycle provides only a few microns of movement, but running at high frequencies, achieves (semi)continuous motion.

Linear quasi-static PiezoLEGS motor[52] operating on walking principle of piezoelectric bimorph legs. Single leg consists of two electrically insulated stacks of piezoelectric material: bimorphs. Application of two independent drive voltages to both stacks results in elongation or bending of the entire leg. Here, motion is a result of bending action of the legs. The sum of voltages cause leg the leg to elongate and the difference causes it bend.

$$\begin{aligned} k_1(v_1 - v_2) &\rightarrow \Delta x(v_1, v_2) \\ k_2(v_1 + v_2) &\rightarrow \Delta y(v_1, v_2) \end{aligned} \qquad (17)$$

Ideal conditions requires constant force in the y direction and linear deflection in x - direction to maintain uniform motion of the rod. These conditions would require the keeping $\Delta y = const$ and Δx as a linear function of time for legs in contact with rod. During the time without contact with rod legs must return to initial position. These requirements could be represented as a desired motion of the tip of the in the (x, y) plane. If the (x, y) trajectories for the leg are arbitrarily defined, as some periodic closed curves r_i that it can be written in parametric form as[52]

$$r_i := \begin{cases} f_{xi} \\ f_{yi} \end{cases} \quad kT \le t \le (k+1)T, k = 1,2,3....... \qquad (16)$$

The proposed approach allows definition of the legs' movement in x-direction independently of the motion in the y-direction. That allows synchronization of motion of certain numbers of legs or delaying motion of some legs, while obtaining desired (x, y) motion. For identical periodic trajectories of legs, the f_{xi} and f_{yi} have to be periodic functions with period T and satisfy

$$\begin{aligned} f_{xi}(t) &= f_{xj}(t + \delta) \\ f_{yi}(t) &= f_{yj}(t + \delta); i \ne j \end{aligned} \qquad (17)$$

where δ is time delay. By changing period T the frequency of repetition of these cyclical motion can be changes and that way the velocity of the rod can be controlled.

For motor with n legs the motion of the legs with supply voltages can be expressed in the following form[52]

$$\begin{aligned} v_{i1} &= \alpha_i (f_{xj} + f_{yj}) \\ v_{i2} &= \alpha_i (f_{xj} - f_{yj}); i = 1,..., n \end{aligned} \qquad (18)$$

Such a formulation would allow to determine supply voltages from relationship (18) as function of the $(\Delta x; \Delta y)$ motion - thus establishing a functional relationship between motor's legs. While such formulation allows controlling the motion it does not offer obvious formulation of the force control.

It would be interesting to try application of this idea to the legged robots. For them the specification of the (x, y) trajectory is more complex especially for motion on uneven terrain in which the functions f should depend on interaction force and the desired pattern.

5. Conclusions

In this paper discussion is concentrated on new technologies that may, in author's view, present new challenges in motion control system design and application. The acceleration control as a basic framework for motion control is discussed in some details along with challenges associated to generalized disturbance observer design as a main part of the acceleration controller. Presentation of the control design for functionally related systems is given in order to show the unified treatment of control design for single task in a multibody system or a task that represent collective action of a collection of multibody systems. human-in-the-llop, cyber-physical-systems technologies along with requirements for more autonomous action of the systems are new challenges for motion control design. The ways human as a part of the control loop is treated may soon be an issue that will determine overall design.

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