IEEJ Journal of Industry Applications
Vol.6 No.2 pp.107–116 DOI: 10.1541/ieejjia.6.107

Paper

Challenges in Motion Control Systems

Asif Šabanović[*a)] Non-member

(Manuscript received April 25, 2016, revised Aug. 4, 2016)

Motion control technology is making its way into the unstructured world inhabited by humans. It allows development of applications beyond the structured environment of an industrial plant. Such applications of motion control technology require shifting focus to the models, control strategies and algorithms needed for systems to work, interact, and cooperate with humans or other artifacts in an unstructured environment. Real-world haptic interactions are becoming an important technology with potential application in many different fields like surgery, teleoperation, cooperative work, microsystems, and education. These developments are leading to numerous challenges that need to be solved in order to develop practical and competent systems that support the human operator, and are fault tolerant, safe, easy to use, and capable of adapting to long-term changes in the environment. This paper discusses a number of the emerging issues within motion control technology, including but not limited to new algorithms that allow concurrent force/position control, human-in-the loop control, control in functionally related systems and haptics over internet.

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

1. Section

Motion control is a technology that makes possible advances in many fields like high-tech manufacturing systems, high precision motion, advanced automotive applications, robotics, mechatronics, haptics, biomechanical, medical and welfare applications, to name some. In many of these applications motion control is enabling machines (artifacts, robots) to perform in 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 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)]" encompasses large variety of the systems, but it still does not include systems in which human appears as a part of a 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 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 to record and then play back the haptic information would substantially change a way of the training people or preserving a way specialists are executing tasks in which haptic information is important [(6)]. These and other applications require motion control algorithms to maintain safety and controlled interaction with humans and environment, thus controlling the motion and the interaction forces simultaneously. 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 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

a) Correspondence to: Asif Šabanović. E-mail: asif@sabanciuniv.edu
[*] Sabancı University
FENS, Orta Mahalle-Tuzla, Universite Cad. 27, 34956 Istanbul, Turkey

nanometer ranges, along with an inclination toward miniaturization, dynamics streamlining, and interference immunity are pushing the physical limitations of electromagnetic drive systems. There is a need to search for new actuators for very demanding applications. 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, drug delivery devices, 3D scanning [15] optics, measurement etc. because of inherent advantages for equipment design.

The growth of the area of motion control application are opening numerous challenging issues to be solved in order to develop practical and competent 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.

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]

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

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 elements, hence $A^-\leq\|\mathbf{A}(\mathbf{q})\|\leq A^+$, where A^-, A^+ are two known scalars with bounds $0<A^-\leq A^+$; $\mathbf{b}(\mathbf{q},\dot{\mathbf{q}})\in\Re^{n\times 1}$ stands for vector Coriollis forces, viscous friction and centripetal forces and is bounded by $\|\mathbf{b}(\mathbf{q},\dot{\mathbf{q}})\|\leq b^+$; $\mathbf{g}(\mathbf{q})\in\Re^{n\times 1}$ stands for vector of gravity terms bounded by $\|\mathbf{g}(\mathbf{q})\|\leq g^+$; $\boldsymbol{\tau}\in\Re^{nx1}$ stands for vector of generalized joint forces bounded by $\|\boldsymbol{\tau}\|\leq\tau^+$, $\mathbf{y}(\mathbf{q})\in\Re^{m\times 1}$ 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 $\|\mathbf{\Phi}^T\boldsymbol{\lambda}\|\leq\vartheta^+$ 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 $\det(\mathbf{A}(\mathbf{q}))\neq 0$, $\forall\mathbf{q}\in D^q$ allows that (1) could be rearranged into

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

The $\boldsymbol{\tau}_{\ddot{q}}$, $\boldsymbol{\tau}^{dis}_{\ddot{q}}$ stands for the acceleration induced by the generalized forces $\boldsymbol{\tau}$ and the "disturbance acceleration" induced by the disturbance forces $\boldsymbol{\tau}^{dis}_{q}=\mathbf{b}+\mathbf{g}+\mathbf{\Phi}^T\boldsymbol{\lambda}$. 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 $\det(\mathbf{A}_n(\mathbf{q}))\neq 0$, $\forall\mathbf{q}\in D^q$, (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 $(\mathbf{b}+\mathbf{g}+\mathbf{\Phi}^T\boldsymbol{\lambda})$ but also due to the uncertainties $\Delta\mathbf{A}(\mathbf{q})$. The term $\boldsymbol{\tau}^{dis}_{\ddot{q}}=\mathbf{A}_n^{-1}(\Delta\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{b}+\mathbf{g}+\mathbf{\Phi}^T\boldsymbol{\lambda})$ stands for the bounded matched generalized disturbance $\|\boldsymbol{\tau}^{dis}_{\ddot{q}}\|\leq\tau^{+dis}$ consisting not only of the coupling and projection of external forces but also on the parameter variation. In the further text (2) will be treated as a general expression allowing to handle, under certain conditions, systems with and without parameter uncertainties.

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

$$\begin{aligned}&\dot{q}_i=v_i,\\&\ddot{q}_i=\dot{v}_i=\tau^i_{\ddot{q}}(\boldsymbol{\tau},\mathbf{q})-\tau^{idis}_{\ddot{q}};\quad i=1,\ldots,n\\&y_i=y_i(\mathbf{q})\end{aligned} \quad \cdots\cdots (3)$$

Both $\tau^i_{\ddot{q}}$ and $\tau^{idis}_{\ddot{q}}$ 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 (in some cases it may depend on acceleration also). 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]. The dimension of the output may not be equal to the dimension of the control.

2.1 Acceleration Control The design assumes finding the best controller such that the performance is within specification for all prescribed situations (disturbances and system variations). The system dynamics (2) and (3) suggest a possibility to enforce desired configuration space acceleration in the system. For 1 dof system under assumption that $(v_i,\tau^i_{\ddot{q}})$ are measured and that disturbance can be modeled by $\dot{\hat{\tau}}^{idis}_{\ddot{q}}=0$, generalized disturbance $\tau^{idis}_{\ddot{q}}$ can be estimated by the dynamic system $\dot{z}_i=l_i(\tau^i_{\ddot{q}}-z_i+l_iv_i)$, $\hat{\tau}^{idis}_{\ddot{q}}=z_i-l_iv_i$, $l_i>0$ and may be expressed in the form $\dot{\hat{\tau}}^{idis}_{\ddot{q}}+l_i\hat{\tau}^{idis}_{\ddot{q}}=l_i\tau^{idis}_{\ddot{q}}$. 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 $\hat{\tau}^{idis}_{\ddot{q}}=Q_{qi}\tau^{idis}_{\ddot{q}}$, where Q_{qi} stands for a filter [17]. Applying the same design for system (2) the generalized disturbance vector $\hat{\boldsymbol{\tau}}^{dis}_{\ddot{q}}=[\hat{\tau}^{1dis}_{\ddot{q}}\ \ldots\ \hat{\tau}^{ndis}_{\ddot{q}}]^T$ 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 [17]. By expressing the control input as $\boldsymbol{\tau}_{\ddot{q}}=\ddot{\mathbf{q}}^{des}+\hat{\boldsymbol{\tau}}^{dis}_{\ddot{q}}$, where $\hat{\boldsymbol{\tau}}^{dis}_{\ddot{q}} = \mathbf{Q}_q \boldsymbol{\tau}^{dis}_{\ddot{q}}$ stands for generalized disturbance vector, and $\ddot{\mathbf{q}}^{des}$ stand for desired acceleration, the dynamics (2) reduces to

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

Design of the filter $\mathbf{Q}_q$ may enforce $\boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}^{dis}_{\ddot{q}}) \approx \mathbf{0}$. 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.

With assumption that $\boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}^{dis}_{\ddot{q}}) \approx \mathbf{0}$ selection of desired acceleration as $\ddot{\mathbf{q}}^{des} = \ddot{\mathbf{q}}^{ref} - \mathbf{K}_D(\dot{\mathbf{q}}^{ref} - \dot{\mathbf{q}}) - \mathbf{K}_P(\mathbf{q}^{ref} - \mathbf{q})$, is straight forward. The tracking of the reference $\mathbf{q}^{ref}$ is guaranteed. The $(\ddot{\mathbf{q}}^{ref} - \ddot{\mathbf{q}}) + \mathbf{K}_D(\dot{\mathbf{q}}^{ref} - \dot{\mathbf{q}}) + \mathbf{K}_P(\mathbf{q}^{ref} - \mathbf{q}) = \boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}^{dis}_{\ddot{q}}), \mathbf{K}_D, \mathbf{K}_P > 0$ governs closed loop dynamics. The importance of the disturbance estimation is apparent and it will be discussed in more details in section 2.3.

2.2 Output Control In the subsection 2.1 we have been discussing the configuration space control assuming the known reference. In practical motion control systems, the $\mathbf{y}(\mathbf{q}) \in \Re^{m\times 1}$ stands for the control output and may have different physical mature. As it will be shown 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. As already mentioned it may be function of the position and velocity and sometimes even acceleration and in general may have dimension different from the dimension of the configuration space control. For system (4) and known 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

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

where $\mathbf{J} \in \Re^{m\times n}$ stands for Jacobian, assumed to be a full row rank matrix, $\mathbf{f}^{com}_{\ddot{x}}$, $\mathbf{f}^{dis}_{\ddot{x}}$ stand for the operation space acceleration control and disturbance inputs. Note that components of generalized disturbance $\mathbf{f}^{dis}_{\ddot{x}}$ can be estimated the same way as the configuration space generalized disturbance $\boldsymbol{\tau}^{dis}_{\ddot{q}}$(by assuming $\dot{\hat{f}}^{idis}_{\ddot{x}} = 0$, with $(f^i_{\ddot{x}}, \dot{x}_i)$, is measured, i-th component of $\mathbf{f}^{dis}_{\ddot{x}}$ can be estimate, by $\dot{z}_i = l_i(f^i_{\ddot{x}} - z_i + l_i\dot{x}_i)$, $\hat{f}^{idis}_{\ddot{x}} = z_i - l_i\dot{x}_i$, $l_i > 0$ and may be expressed in the form $\dot{\hat{f}}^{idis}_{\ddot{x}} + l_i\hat{f}^{idis}_{\ddot{x}} = l_i f^{idis}_{\ddot{x}}$). Note that $\ddot{\mathbf{y}}^{ref}(t)$, if known can be excluded from the estimation. Similarly as in the configuration space control the disturbance vector can be expressed as $\hat{\mathbf{f}}^{dis}_{\ddot{x}} = \mathbf{Q}_f \mathbf{f}^{dis}_{\ddot{x}}$, where $\mathbf{Q}_f$ stands for a filter.

By expressing configuration space acceleration control input as $\mathbf{f}^{com}_{\ddot{x}} = \ddot{\mathbf{x}}^{des} + \hat{\mathbf{f}}^{dis}_{\ddot{x}}$, where, and $\ddot{\mathbf{x}}^{des}$ stands for desired error acceleration, yields

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

For $\boldsymbol{\varepsilon}_f(\mathbf{Q}_f, \mathbf{f}^{dis}_{\ddot{x}}) \approx \mathbf{0}$ 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 $\ddot{\mathbf{x}} + \mathbf{K}_D\dot{\mathbf{x}} + \mathbf{K}_P\mathbf{x} = \boldsymbol{\varepsilon}_f(\mathbf{Q}_f, \mathbf{f}^{dis}_{\ddot{x}})$. The same design procedure is applicable if design takes system description (2) instead (4). In that case the operational space disturbance is expressed as $\mathbf{f}^{dis}_{\ddot{x}} = -(\dot{\mathbf{J}}\dot{\mathbf{q}} - \mathbf{J}\tau^{dis}_{\ddot{q}} - \ddot{\mathbf{y}}^{ref}(t))$.

From $\mathbf{f}^{com}_{\ddot{x}} = \mathbf{J}\ddot{\mathbf{q}}^{des}$ the desired configuration space acceleration can be determined as $\ddot{\mathbf{q}}^{des} = \mathbf{J}^{\#}\mathbf{f}^{com}_{\ddot{x}}$ or $\ddot{\mathbf{q}}^{des} = \mathbf{J}^{\#}(\ddot{\mathbf{x}}^{des} + \hat{\mathbf{f}}^{dis}_{\ddot{x}})$, where $\mathbf{J}^{\#} \in \Re^{n\times m}$ is the right generalized pseudoinverse, and the configuration space generalized forces can be expressed as $\boldsymbol{\tau} = \mathbf{A}(\mathbf{J}^{\#}(\ddot{\mathbf{x}}^{des} + \hat{\mathbf{f}}^{dis}_{\ddot{x}}) + \hat{\boldsymbol{\tau}}^{dis}_{\ddot{q}})$. The generalized pseudoinverse $\mathbf{J}^{\#} = \mathbf{W}^{-1}\mathbf{J}^T(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^T)^{-1}\mathbf{J}$ is minimizing $\Pi_W = 0,5\dot{\mathbf{q}}^T\mathbf{W}\dot{\mathbf{q}}$ under constraints $\dot{\mathbf{x}} = \mathbf{J}\dot{\mathbf{q}}$. Selection of $\mathbf{W}$ can be regarded as a design parameter.

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

(i) the configuration space acceleration control (inner loop) is selected first (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 steps: one for the generalized disturbance rejection - effectively acceleration control. In this stage design of the generalized disturbance observer that has small (or known) estimation error is a dominant design issue. In the second step a controller is designed to assure desired closed loop performance.

Essentially, both steps relay on the acceleration control and the design procedure is the same. In the second step while selecting $\ddot{\mathbf{x}}^{des}$ the dynamics $\ddot{\mathbf{q}} = \ddot{\mathbf{q}}^{des} - \boldsymbol{\varepsilon}_q(\mathbf{Q}_q, \boldsymbol{\tau}^{dis}_{\ddot{q}})$ could be taken into account.

2.3 Disturbance Observer[17]–[25] The key idea of a generalized disturbance observer is a design of an autonomous dynamical system that generates the disturbances[17][18]. In the frequency range for which estimation errors are small the generalized disturbance feed makes the real plant behave close to the nominal plant model. Imperfection of the disturbance estimation leads to the discrepancies of the ideal and achieved system.

In order to understand the issues related to the generalized disturbance design let us, for the sake of simplicity, take a look at a SISO plant with estimated disturbance feed to the system input. In frequency domain the SISO plant $q = P(\tau_{\ddot{q}} - \tau^{dis}_{\ddot{q}})$ with disturbance feed $\hat{\tau}^{dis} = Q\tau^{dis}$ and nominal plant model P_n, can be represented as[7]

$$q = P_n \frac{1}{P^{-1}P_n(1-Q) + Q}\ddot{q}^{des} - P_n \frac{(1-Q)}{P^{-1}P_n(1-Q) + Q}\tau^{dis}_{\ddot{q}} \quad \cdots\cdots (7)$$

The dynamics in the control loop and in the disturbance loop look quite complex. For selected nominal plant 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 - thus leading to a realizable transfer function $P_n^{-1}Q$.

(b) *Global shape*—As disturbances should be rejected as much as possible, from (7) follows that ideally Q should be unity, but the requirement on the relative degree contradicts this. The compromise is in selecting $Q \approx 1$ within the frequency range in which disturbance is predominant or need to be rejected.

(c) *Model misfit*—Q being designed as a low-pass filter at low frequencies gives $Q \approx 1$ so (7) reduces to $q = P_n\ddot{q}^{des} - 0 \times P\tau_{\ddot{q}}^{dis}$, thus as expected, behavior of the system is described by the nominal plant. At high frequencies $Q \approx 0$ and (7) reduces to $q = P\ddot{q}^{des} - P\tau_{\ddot{q}}^{dis}$, thus behavior is described by the original plant.

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 $(q, \tau_{\ddot{q}})$ thus in can be designed as $z = \hat{\tau}_{\ddot{q}}^{dis} = W_1\tau_{\ddot{q}} - W_2 q$, 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)

$$q = P_n \frac{P_n^{-1}}{P^{-1}(1-W_1)+W_2}\ddot{q}^{des} - P\frac{P^{-1}W_1}{P^{-1}(1-W_1)+W_2}\tau_{\ddot{q}}^{dis}$$
$$q = P_n Q_q^{con}\ddot{q}^{des} - PQ_q^{dis}\tau_{\ddot{q}}^{dis} \quad \cdots\cdots (8)$$

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.

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 desired transfer function (may be non-proper). Let the real observer output is expressed as $\hat{z} = W_1\tau_{\ddot{q}} + W_2 q$, with W_1, W_2 as proper transfer functions. By allowing that the output estimation error can take form $\varepsilon_z = z - \hat{z} = W_d\tau_q^{dis}$ one can determine conditions that W_1, W_2 should satisfy in the following form $P(W_N - W_2) - W_1 = 0$ and $P(W_N - W_2) - W_d = 0$.

Getting right disturbance compensation is one of the central issues in the acceleration 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:

a) most of the design procedures are developed for so called matched disturbances, which are common in motion control systems. The new tools for analysis and design of DOB and DOB based control systems are still needed. The coherent design procedure for unmatched disturbance is yet to be developed (21).

b) in most of the cases disturbance observer is designed in the continuous time and then implemented in the discrete time. This may not be the best solution, so the discrete-time design of the disturbance observer need to be examined in more details (24).

c) 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) this is an important design opportunity if the predominant disturbance behavior is known.

d) selection of the plant and the nominal models is critical due to complex dynamics of the loop with estimated disturbance feed. The problem is enhanced 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.

e) 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 (26).

In addition to disturbance rejection and robustness, the disturbance observer can be applied as other areas like fault detection, communication etc.

3. Control of Functionally Related Systems

The idea of functionally related systems had been proposed in (27)(28). The most common ways had been defined in so called common and differential mode (27)–(33). The idea of functionally related systems had been further expanded (7)(17) to include relationship defined by a linear or nonlinear function of the configuration space coordinates or system outputs. The approach 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 systems' coordinates or outputs.

A set of the functions that is being executed at a particular moment of time defines current system task. This allows extended formulation of the system task which can be defined for a set of systems that are of different nature and different functionality (for example bilateral control, aggregation of mobile systems, etc.).

The selection of the functional relationship is not straight forward. The coherent design procedure in general case is yet to be developed. Natural requirement is that the system state obtained as a solution of the set of functions should be a realizable by the system. Such 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.

3.1 Redundant Task Consider a $n-$ dof fully actuated mechanical system. It could be a single multi body system or a collection of m systems that combined have $n-$ dof. Let set of m functions expressed by vector $\mathbf{y} = [\mathbf{y}_1 \ \dots \ \mathbf{y}_m]^T$

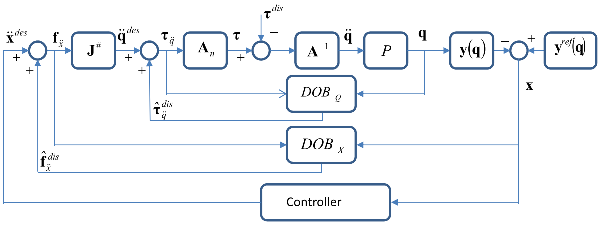


Fig. 1. Structure of the Acceleration Control based task control system

together with their references $\mathbf{y}^{ref} = [\mathbf{y}_1^{ref} \ \ldots \ \mathbf{y}_m^{ref}]^T$ describe desired operation of the system. Here functions $\mathbf{y}_i(\mathbf{q}) \in \Re^{k_i \times 1}$, and $\mathbf{y}_i^{ref}(\mathbf{q}) \in \Re^{k_i \times 1} i = 1, \ldots, m$ with $\sum_{i=1}^{m} k_i = n$, all $\mathbf{y}_i(q)$ and $\mathbf{y}_i^{ref}(\mathbf{q})$ are assumed two times differentiable and Jacobians $\partial \mathbf{y}_i(\mathbf{q})/\partial \mathbf{q} = \mathbf{J}_{yi}$ have full row rank. In addition we may require that control of functions $\mathbf{y}_i$ are dynamically decoupled from each other.

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. The closed loop dynamics for single task $\mathbf{y}_i \in \Re^{k_i}$, $k_i < n$ with the control input $\mathbf{f}_{\ddot{x}i}^{com} = \ddot{\mathbf{x}}_i^{des} + \hat{\mathbf{f}}_{\ddot{x}i}^{dis}$ becomes $\ddot{\mathbf{x}}_i = \ddot{\mathbf{x}}_1^{des} + \boldsymbol{\varepsilon}_f(\mathbf{f}_{\ddot{x}i}^{dis})$.

The desired configuration space acceleration can be expressed as

$$\ddot{\mathbf{q}}^{des} = \mathbf{J}_i^{\#}(\ddot{\mathbf{x}}_i^{des} - \dot{\mathbf{J}}_i\dot{\mathbf{q}} + \mathbf{J}_i\boldsymbol{\varepsilon}_q(\boldsymbol{\tau}_{\ddot{q}}^{dis})) - \boldsymbol{\varepsilon}_f(\mathbf{f}_{\ddot{x}}^{dis}) + (\mathbf{I} - \mathbf{J}_i^{\#}\mathbf{J}_i)\ddot{\mathbf{q}}_0 \quad \cdots\cdots (9)$$

Where $\ddot{\mathbf{q}}_0 \in \Re^{n \times 1}$ is arbitrary acceleration in configuration space. By plugging (9) into (4) the overall system dynamics can be expressed as

$$\begin{aligned} &(\mathbf{I} - \mathbf{J}_i^{\#}\mathbf{J}_i)\ddot{\mathbf{q}} = (\mathbf{I} - \mathbf{J}_i^{\#}\mathbf{J}_i)\ddot{\mathbf{q}}_0 + \mathbf{J}_i^{\#}\mathbf{J}_i\boldsymbol{\varepsilon}_q(\boldsymbol{\tau}_{\ddot{q}}^{dis}) \\ &\ddot{\mathbf{x}}_i = \ddot{\mathbf{x}}_1^{des} + \boldsymbol{\varepsilon}_f(\mathbf{f}_{\ddot{x}i}^{dis}) \end{aligned} \quad \cdots\cdots (10)$$

From (10) follows that at the same time additional tasks such that $\sum_{j=1}^{m-1} k_j = n - k_i$ could be executed, in addition to the redundant task. The structure of the control system is depicted in Fig. 1.

3.2 Concurrent Multi-Task Control From (5) the dynamics of the task error $\mathbf{x} = (\mathbf{y} - \mathbf{y}^{ref}) \in \Re^{n \times 1}$ can be, written as

$$\begin{aligned} &\ddot{\mathbf{x}} = \mathbf{J}\ddot{\mathbf{q}}^{des} - \mathbf{f}_{\ddot{x}}^{dis} = \mathbf{f}_{\ddot{x}}^{com} - \mathbf{f}_{\ddot{x}}^{dis}; \mathbf{J}_i = \frac{\partial \mathbf{x}_i}{\partial \mathbf{q}}, i = 1, \ldots, m \\ &\mathbf{f}_{\ddot{x}}^{com} = [[\mathbf{f}_{\ddot{x}1}^{com}]^T \ \ldots \ [\mathbf{f}_{\ddot{x}m}^{com}]^T]^T; \mathbf{f}_{\ddot{x}}^{dis} = [[\mathbf{f}_{\ddot{x}1}^{dis}]^T \ \ldots \ [\mathbf{f}_{\ddot{x}m}^{dis}]^T]^T; \\ &\mathbf{J} = [\mathbf{J}_1^T \cdots \mathbf{J}_m^T]^T \in \Re^{n \times n}; \end{aligned} \quad \cdots\cdots (11)$$

By assumption Jacobian $\mathbf{J}$ is full rank matrix. The desired configuration space acceleration can be expressed $\ddot{\mathbf{q}}^{des} = \mathbf{J}^{-1}\mathbf{f}_{\ddot{x}}^{com}$. The control distribution matrix $\mathbf{J}^{-1}$ is not block diagonal and consequently the tasks are dynamically coupled.

The operational constraints may require enforcement of the hierarchy in the tasks execution. The simplest example is relationship between task and constraints - task could be executed only if constraints are not violated. Selection of the JacobianJas shown in (12) leads to dynamical decoupling of tasks and allows fulfilling the priority requirements [7][17][34][35] with $\boldsymbol{\Omega}_i = \mathbf{J}_i\mathbf{N}_{J_1,\ldots,J_{i-1}}$ and, $\mathbf{N}_{J_1,\ldots,J_{i-1}} = (\mathbf{I} - \mathbf{J}_1^{\#}\mathbf{J}_1 - \ldots - \mathbf{J}_{i-1}^{\#}\mathbf{J}_{i-1})$

$$\mathbf{J} = \begin{bmatrix} \mathbf{J}_1 \\ \boldsymbol{\Omega}_2(\mathbf{J}_2) \\ \cdots \\ \boldsymbol{\Omega}_m(\mathbf{J}_m) \end{bmatrix}; \ \ddot{\mathbf{q}}^{des} = [\mathbf{J}_1^{\#} \ \boldsymbol{\Omega}_2^{\#} \ \ldots \ \boldsymbol{\Omega}_m^{\#}] \begin{bmatrix} \mathbf{f}_{\ddot{x}1}^{com} \\ \mathbf{f}_{\ddot{x}2}^{com} \\ \cdots \\ \mathbf{f}_{\ddot{x}m}^{com} \end{bmatrix} \cdots\cdots (12)$$

Here $(\cdot)_k^{\#}$ are generalized weighted pseudoinverse matrices associated with *k-th* sub-task.

Proposed control, with some modifications due to implementation peculiarities, has been used for cooperation control of articulated and mobile robots [28]. 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.

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

- 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 task could be defined in a acceleration space [7][17][34][35] as $\mathbf{x}(\ddot{\mathbf{q}}, t)$. How to handle the control in the case that part of the task is defined as $\mathbf{x}(\mathbf{q}, t)$ and the other part as $\mathbf{x}(\ddot{\mathbf{q}}, t)$ is less investigated in the literature;
- (12) opens an opportunity for the dynamical changes 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.

This short analysis shows that the acceleration control works equally well for the systems described in the configuration and in operational spaces. The design procedure and resulting controller are structurally the same and even the structure of the generalized disturbance estimation is the same.

4. Some Applications of Motion Control

4.1 Concurrent Position Tracking and Force Control

The capability of machines to interact with humans is seen as a key of next innovation in motion control systems. The sophisticated interaction with environment and/or with operator includes transmission of the interaction force- real-world haptic sensing - to the operator [36]–[38] or modification of motion due to interaction. This would require incorporation of the force control within the machine controller and design inputs as function of position and force (or stiffness in some cases) [7]. The need to modify motion due to the interaction force is already a necessity for preserving safety in contact with human.

For single dof system the position tracking can be realized if the output error $e = q^{ref} - q$ is forced to satisfy $\dot{e} + Ce = \sigma = 0, C > 0$. The generalized error σ may be interpreted as a force pulling system from its current position $q(t)$ to reference position $q^{ref}(t)$ with stiffness C and unity damping. Interaction force with environment with environment in position $q_e(t)$ can be expressed as $D_e\dot{e}_e + Ke_e = f_e, e_e = q_e - q$. In contact point $q_e \neq q^{ref}$ the "action-reaction" law must be satisfied thus $\sigma(q, q^{ref}) + f_e(q_e, q) = \sigma_e(q, q_e, q^{ref}) = 0$ must be maintained. Thus if instead of position generalized error the $\sigma(t) + \lambda f_e(t) = \sigma_e^*(q, f_e, t)$, $\lambda > 0$ is used in the control input design, then for $\sigma_e^* = 0$ the force balance leads to

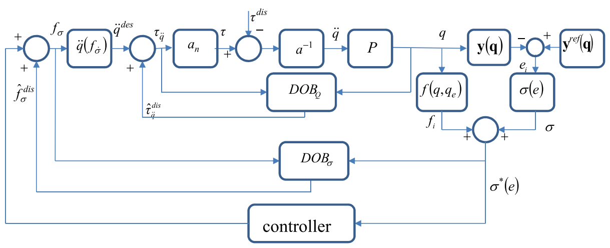


Fig. 2. Structure of the concurrent position - force control

$\sigma(q,t) = -\lambda f_e(t)$ 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.

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

4.2 Real-World Haptics [(3)–(5)(36)–(38)] When a sensitive task is executed at a distant location from operator the haptic information (interaction force) should be transmitted to the operator. In such system the synchronization of position (position tracking) and artificial realization of law of action and reaction (force feedback to operator) are required. These requirements may be formulated in the form of some functions of states of the two systems tracking their references. Having master side (in contact with operator) variable labeled by suffix m and slave side variable labeled by suffix s the operational requirements of bilateral system will be realized if operational space errors are enforced to have stable zero solution.

$$x_m(q_m) - \alpha x_s(q_s) = y_x(q_m, q_s) \underset{\substack{t\to\infty \\ t\geq t_0}}{\rightarrow} 0 \Rightarrow x_m(q_m) \rightarrow \alpha x_s(q_s)$$
$$f_m(q_m) + \beta f_s(q_s) = y_f(q_m, q_s) \underset{\substack{t\to\infty \\ t\geq t_0}}{\rightarrow} 0 \Rightarrow f_m(q_m) \rightarrow -\beta f_s(q_s)$$
$$\alpha, \beta > 0 \cdots\cdots (13)$$

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

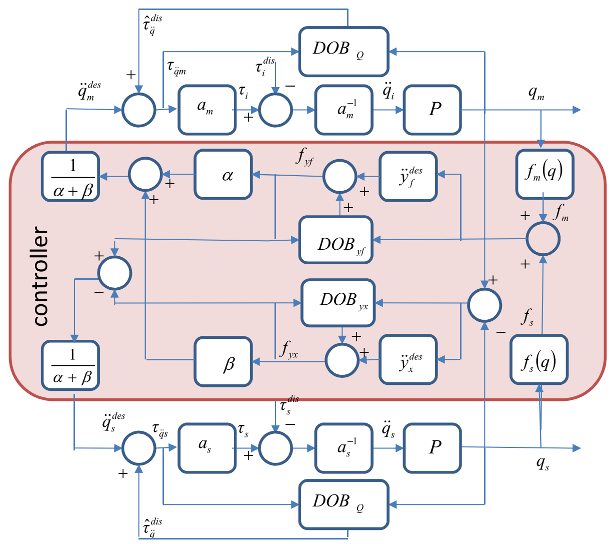


Fig. 3. Structure of bilateral control systems

$$\ddot{y}_x(q_m, q_s) = \ddot{q}_m^{des} - \alpha\ddot{q}_s^{des} - (\varepsilon_m^{dis} - \alpha\varepsilon_s^{dis}) = f_{yx}^{des} - f_{yx}^{dis}$$
$$\ddot{y}_f(q_m, q_s) = \ddot{q}_m^{des} + \beta\ddot{q}_s^{des} + (\varepsilon_m^{dis} + \beta\varepsilon_s^{dis} + f_{ms}^{dis}) = f_{yf}^{des} - f_{yf}^{dis} \cdots\cdots (14)$$

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 determined from $(\alpha+\beta)\ddot{q}_s^{des} = -f_{yx}^{des} + f_{yf}^{des}$ and $(\alpha+\beta)\ddot{q}_m^{des} = \beta f_{yx}^{des} + \alpha f_{yf}^{des}$, . The topology of the system is depicted in Fig. 3. It should be noted here that (13) 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. In [(3)–(5)] the functional relationship (13) is expressed in the terms of master and slave system accelerations. The desired accelerations are obtained in a way similar to one shown above.

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)(39)(43)–(45)]. How to treat bilateral systems with variable delay is still open research question.

The possibility of the realistic reflection of the manipulation force along with control of the displacement opens very interesting application area in recording the haptic information, thus allowing preservation of the haptic sense realized while executing task, and later using that information to repeat the same motion-haptic relationship by machine.

4.3 Human-in-the-Loop Control Safety-critical technical systems interact with human being, and the human operator's role is essential to the correct working of the system [40][41]. Examples of such systems include fly-by-wire control systems, automobiles with driver assistance systems, medical devices etc. The role of the human operator varies very much in these systems. The direct operation of the system in master-slave operation is already discussed in the section 4.3. The concurrent motion-force control and distance interaction realized by real-world haptic present a special human-in-the-loop system systems with wide range of applications. Here we would like to draw attention on the systems with certain level of autonomy and the interaction of the human and (semi)autonomous systems.

The degree of autonomy in a system (process) operation is a function of the predictability of system's (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 entirely how external influences can affect the control system, thus to have a complete description of the system behavior. The luck of completeness of the description of the system function along with uncertainties related to the control implementation in software and the unpredictability of the components' error lead to operational conditions that may not be taken into account. That limits the possibility to reflect in the operation specification stage 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. In such a situation interaction of the human operator may be required and must be integrated in the systems design phase in order to be coded in the system software.

At present, there is no systematic methodology for synthesis of a combination of human and autonomous control from high-level specifications [10][42]. Major research challenges of systems involving human-in-the-loop control are:

- understanding the complete spectrum of human-in-the-loop control and possibility to correctly specify operational criteria,
- modeling human behavior and incorporation of these models into the formal feedback control;
- formalization of human-in-the-loop control systems and the problem of synthesizing such controllers from high-level specifications.

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 the challenges facing design of the human-in-the loop control systems. Understanding and maximizing the collaboration between the autonomous 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.

4.4 Cyber-Physical-Systems In the last few years the so-called "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.

Real-world haptics technology achieves remote motion and/or amplification of the motion with haptic sense thus supporting work at distance that is beyond human abilities. These systems, with concurrent motion-force control and distance interaction, allows relocation of the work place for human. That may be required if the real task execution environment is dirty, dangerous; or the tasks execution needs haptic capabilities (like safe contact motion, manipulation in the micro world where human senses are not compatible etc.); or if during the task execution intuitive decision by human is required.

The haptic interaction at distance is becoming very interesting field of research with a potential to create a new paradigm - realization of the Haptic over Internet. Obviously that would require research effort not only in the motion control systems but in other fields as well.

The haptic interaction is information rich and requires secure high bandwidth communication. The haptic over internet would require special communication networks/protocols or some other means that would allow very short information exchange delays (optimally below 1 millisecond). The questions like scheduling, network security, fault tolerance, etc., are emerging challenges in haptics over internet. The real-time haptics implementation on limited resources devices, and complexity due to the large number of possibly unreliable agents involved [46] add to the complexity of the design of haptic over internet systems.

Research on the ways haptic information is coded for the network communication or for the possible "haptic replay" (compression and representation of data - haptic codec) is essential for real-time internet haptics or the possibility to store haptic data for usage on different place and in different time.

The acceleration based motion control in haptic over internet systems has many advantages [36]–[38]. Still open for research are problems of multi dof systems with delay and physical limitation of the communication systems. While application of the disturbance observer offers significant simplification of the compensated plant dynamics the characterization of the environment beyond the interaction force estimation, is still an open issue. If for example the correct model of environment could be derived than instead of sending force information over internet only parameters of the environment model may be sent and thus significantly relax the

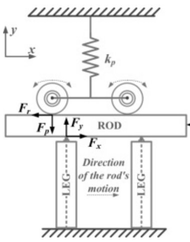


Fig. 4. Schematics of a PiezoLEGS motor

communication traffic.

In CPS systems the level of autonomy and control complexity 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 the 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. 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, micro-dose dispensing, cell penetration and cell imaging in cytopathology, drug delivery devices, 3D scanning) optics, measurement etc. because of inherent advantages for equipment design [(47)–(51)].

Special attention are attracting PZT motors which can provide unlimited motion and very high accuracy. These motions can be conducted in the presence of strong magnetic fields or at very low temperatures. PZT stepper linear motors 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.

Schematics of the PiezoLEGS motor [(53)] is shown in Fig. 4. 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. The sum of voltages cause leg the leg to elongate $k_2(v_1 + v_2) \rightarrow \Delta y(v_1, v_2)$ and the difference causes it bend and generate motion in x direction $k_1(v_1 - v_2) \rightarrow \Delta x(v_1, v_2)$.

To maintain uniform motion of the rod requires constant rode lifting force (in the y direction) and linear deflection in x- direction. 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 leg 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 [(53)] (f_{xi}, f_{yi}) for $kT \leq t \leq (k+1)T$, $k = 1, 2, 3 \ldots$. The definition of the legs' movement in x-direction and the y-direction are set independently. That allows synchronization of motion of certain numbers of legs or delaying motion of some legs, while obtaining desired (x, y) trajectory. For identical periodic trajectories of legs, the f_{xi} and f_{yi} have to be periodic functions with period T and satisfy $f_{xi}(t) = f_{xj}(t + \Delta t)$ and $f_{yi}(t) = f_{yj}(t + \Delta t); i \neq j$ where Δt is the 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 [(53)] $v_{i1} = \alpha_i(f_{xj} + f_{yj})$ and $v_{i2} = \alpha_i(f_{xj} - f_{yj}); i = 1, \ldots, n$. Such a formulation would allow to determine supply voltages 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 x-direction force control.

The legged robots are achieving their propelling in the same way - they generate trajectory of the foots in (x, y, z) space and coordinate the motion of the legs. It would be interesting to try application of legged actuators control to the legged robots. For them the specification of the (x, y, z) trajectories is more complex especially for motion on uneven terrain in which the trajectories must be modified by interaction forces.

5. Conclusions

In this paper discussion is concentrated on 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-loop, 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. The haptics over internet present a big challenge in motion control systems application and opens a possibility of a new paradigm in human-machine interaction, storing and replaying haptic experience.

Acknowledgment

Author would like to acknowledge TÜBİAK project 114M578 for partial support.

References

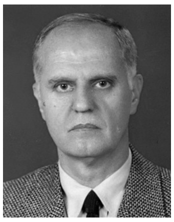
(1) M. Steinbuch: "Design and Control of High Tech Systems", Proceedings of The 2013 American Control Conference, June 17-19, Washington, DC, USA (2013)

(2) H. Fujita, G.S. Buja, and K. Onishi, Recent Advances in Motion Control, Moshon Kontororu No Saishin Gijutsu, ISBN-13: 978-4-526-02854-0, ISBN: 4-526-02854-1 (1990)

(3) K. Ohnishi: "Real World Haptics and Telehaptics for Medical Applications", 2010 IEEE International Symposium on Industrial Electronics (ISIE), 4-7 July 2010, Bari, Italy, pp.11–14 (2010)

(4) S. Sakaino1, A.M. Harsha S. Abeykoon, and K. Ohnishi: "Real World Haptics Applied to Forceps in Robot Surgery", 2010 5th International Conference on Information and Automation for Sustainability (ICIAFs),
(5) S. Katsura and K. Ohnishi: "A Realization of Haptic Training System by Multilateral Control", *IEEE Trans. on Industrial Electronics*, Vol.53, No.6 (2006)
(6) M.I. Tiwana, S.J. Redmond, and N.H. Lovell: "A review of tactile sensing technologies with applications in biomedical engineering, Sensors and Actuators", A: Physical, Vol.179, pp.17–31 (2012)
(7) A. Sabanovic and K. Ohnishi: "Motion Control Systems", Willey Publisher (2011)
(8) D.A. Mindell: "Our Robots, Ourselves. Robotics and the Myths of Autonomy Robotics and the Myths of Autonomy", Viking (2015)
(9) W. Li, D. Sadigh, S. Shankar Sastry, Sanjit A. Seshia Synthesis for Human-in-the-Loop Control Systems, Technical Report No.UCB/EECS-2013-133 (2013)
(10) S. Munir, J.A. Stankovic Chieh-Jan Mike Liang Shan Lin: "Cyber Physical System Challenges for Human-in-the-Loop Control", Proceedings of 8th International Workshop on Feedback Computing, San Jose, USA, June 24-28 (2013)
(11) A. Leeper, K.H.M. Ciocarlie, and L.T.D. Gossow: "Strategies for Human-in-the-Loop Robotic Grasping", Proceedings of HRI'12, March 5–8, 2012, Boston, Massachusetts, USA (2012)
(12) D. Nunes, P. Zhang, and J.S'a Silva: "A survey on Human-in-the-Loop applications towards an Internet of All", DOI 10.1109/COMST.2015.2398816, IEEE Communications Surveys & Tutorials (2015)
(13) Y. Li and Q. Xu: "Design and robust repetitive control of a new parallel kinematic xy piezostage for micro/nanomanipulation", *IEEE/ASME Transactions on Mechatronics*, Vol.17, No.6, pp.1120–1132 (2012)
(14) Z.T.H. Tse, H. Elhawary, M. Rea, B. Davies, I. Young, and M. Lamperth: "Haptic needle unit for MR-guided biopsy and its control", *IEEE/ASME Transactions on Mechatronics*, Vol.17, No.1, pp.183–187 (2012)
(15) Y. Kurita, F. Sugihara, J. Ueda, and T. Ogasawara: "Piezoelectric tweezer-type end effector with force-and displacement-sensing capability", *IEEE/ASME Transactions on Mechatronics*, Vol.17, No.6, pp.1039–1048 (2012)
(16) T. Uzunovic: "Motion Control Design for Functionally Related Systems", PhD Thesis, Sabanci University, Istanbul (2015)
(17) W.-H. Chen, J. Yang, L. Guo, and S. Li: "Disturbance - Observer - Based Control and Related Methods—An Overview", *IEEE Transaction on Industrial Electronics*, Vol.IE-63, No.2 (2016)
(18) K. Ohishi, M. Nakao, K. Ohnishi, and K. Miyachi: "Microprocessor- Controlled DC motor for Load-Insensitive Position Servo System", *IEEE Transaction on Industrial Electronics*, Vol.IE-34, No.1 (1987)
(19) S. Katsura, Y. Matsumoto, and K. Ohnishi: "Modeling of Force Sensing and Validation of Disturbance Observer for Force Control", *IEEE Transaction on Industrial Electronics*, Vol.IE-54, No.1 (2007)
(20) E. Schrijver and J. van Dijk: "Disturbance Observers for Rigid Mechanical Systems: Equivalence, Stability, and Design", Journal of Dynamic Systems, Measurement, and Control DECEMBER 2002, Vol.124 (2002)
(21) Z. Gao: "On the centrality of disturbance rejection in automatic control", ISA Transaction, Vol.53, No.214, 850-857
(22) S.J. Kwon and W.K. Chung: "A Discrete-Time Design and Analysis of Perturbation Observer for Motion Control Applications", *IEEE Transactions on Control Systems Technology*, Vol.11, No.3 (2003)
(23) R. Madońkin and P. Herman: Survey on methods of increasing the efficiency of extended state disturbance observers, ISA Transactions, 56 18–27 (2015)
(24) S. Kwon and W.K. Chung: "A Discrete-Time Design and Analysis of Disturbance Observer for Motion Control Applications", *IEEE Transaction on Control Systems Technology*, Vol.11, No.3 (2003)
(25) L. Chan and F. Naghdy: "David Stirling Extended active observer for force estimation and disturbance rejection of robotic manipulators", Robotics and Autonomous Systems, Vol.61, 2013, pp.1277–12873 (2013)
(26) K.K. Tan, H.F. Dou, and K.Z. Tang: "Precision Motion Control Systems for Ultra-Precision Semiconductor and Electronics Component Manufacturing", In the Proc. of 51st Electronics Component and Technology Conference, May 29-June 01, Orlando FL, USA (2001)
(27) S. Katsura, Y. Matsumoto, and K. Ohnishi: "Realization of "Law of Action and Reaction" by Multilateral Control", *IEEE Transaction on Industrial Electronics*, Vol.52, No.5 (2005)
(28) T. Tsuji, K. Ohnishi, and A. Sabanovic: "A Controller Design Method Based on Functionality", 9th IEEE International Workshop on Advanced Motion Control (AMC), 27 Mar - 29 Mar 2006, Istanbul, Turkey (2006)
(29) S. Katsura and K. Ohishi: "Modal System Design of Multirobot Systems by Interaction Mode Control", *IEEE Transaction on Industrial Electronics*, Vol.54, No.3 (2007)
(30) S. Sakaino, T. Sato, and K. Ohnishi: "Oblique Coordinate Control for Advanced Motion Control Applied to Micro-Macro Bilateral Control", Proceedings of the 2009 IEEE International Conference on Mechatronics. Malaga, Spain (2009)
(31) R. Kubo, T. Shimono, and K. Ohnishi: "Flexible Controller Design of Bilateral Grasping Systems Based on a Multilateral Control Scheme", *IEEE Transaction on Industrial Electronics*, Vol.56, No.1 (2009)
(32) S. Sakaino T. Sato, and K. Ohnishi: "Multi-DOF Micro-Macro Bilateral Controller Using Oblique Coordinate Control", *IEEE Transaction on Industrial Electronics*, Vol.7, No.3 (2011)
(33) S. Hyodo, R. Kubo, and K. Ohnishi: "A Stable Grasping and Manipulating Control Method Based on Grasp Plane", IEEE 32nd Annual Conference on Industrial Electronics, IECON (2006)
(34) O. Khatib, L. Sentis, J. Park, and J. Warren: "Whole body dynamic behavior and control of human-like robots", Intl. J. Robot. res., Vol.1, No.1, 29-44 (2004)
(35) S. Sakaino: "Advanced Motion Control for Tasks in Open Environment", PhD Thesis, Keio University, Japan (2011)
(36) T. Shimoichi and S. Katsura: "Identification and Compensation of Disturbance for Real–World Haptics", The 12th IEEE International Workshop on Advanced Motion Control March 25-27, Sarajevo, BiH (2012)
(37) K. Ohnishi, T. Nozaki, and T. Mizoguchi: "Haptics for Industries", Advanced Motion Control (AMC), 2014 IEEE 13th International Workshop on, MC2014-Yokohama March 14-16, Yokohama, Japan (2014)
(38) D.I. Katzourakis, D.A. Abbink, R. Happee, and E. Holweg: "Steering Force Feedback for Human–Machine-Interface Automotive Experiments", *IEEE Transactions on Instrumentation and Measurement*, Vol.60, No.1 (2011)
(39) H. Sakai and K. Ohnishi: "A Novel Viewpoint in Bilateral Control System with Time-Delay Aiming on Clear Control Goal", 41st Annual Conference of the IEEE Industrial Electronics Society, November 9 – 12, Pacifico Yokohama, Yokohama, Japan (2015)
(40) D.A. Mindell, Our Robots, Ourselves. Robotics and the Myths of Autonomy. Robotics and the Myths of Autonomy. Viking (2015)
(41) W. Li, D. Sadigh, S. Shankar Sastry, and A. Sanjit: Seshia Synthesis for Human-in-the-Loop Control Systems, Technical Report No.UCB/EECS-2013-134
(42) A. Leeper, K.H.M. Ciocarlie, and L.T.D. Gossow: Strategies for Human-in-the-Loop Robotic Grasping, Proceedings of HRI'12, March 5–8, Boston, Massachusetts, USA (2012)
(43) K. Natori and K. Ohnishi: "A design method of communication disturbance observer for time-delay compensation, taking the dynamic property of network disturbance into account", *IEEE Trans. Ind. Electron.*, Vol.55, No.5, pp.2152–2168 (2008)
(44) K. Natori, T. Tsuji, K. Ohnishi, A. Hace, and K. Jezernik: "Time-delay compensation by communication disturbance observer for bilateral teleoperation under time-varying delay", *IEEE Trans. Ind. Electron.*, Vol.57, pp.1050–1062 (2010)
(45) W. Zhang, M. Tomizuka, Y.-H. Wei, Q. Leng, S. Han, and A.K. Mok: "Robust Time Delay Compensation in a Wireless Motion Control System with Double Disturbance Observers", 2015 American Control Conference, palmer House Hilton, July 1-5, Chicago, IL, USA 5294-5299 (2015)
(46) I. Kim and T. Kim: "Guaranteeing Isochronous Control of Networked Motion Control Systems Using Phase Offset Adjustment", Sensors (Basel). 2015 Jun; 15(6): PMCID: PMC4507583, 13945–13965, Published online 2015 Jun 12. doi: 10.3390/s150613945
(47) D.H. Wang, Q. Yang, and H.M. Dong: "A monolithic compliant piezoelectricdriven microgripper: Design, modeling, and testing", *IEEE/ASME Transactions on Mechatronics*, Vol.18, No.1, pp.138–147 (2013)
(48) Y. Li and Q. Xu: "Design and robust repetitive control of a new parallel kinematic xy piezostage for micro/nanomanipulation", *IEEE/ASME Transactions on Mechatronics*, Vol.17, No.6, pp.1120–1132 (2012)
(49) Z.T.H. Tse, H. Elhawary, M. Rea, B. Davies, I. Young, and M. Lamperth: "Haptic needle unit for MR-guided biopsy and its control", *IEEE/ASME Transactions on Mechatronics*, Vol.17, No.1, pp.183–187 (2012)
(50) Y. Kurita, F. Sugihara, J. Ueda, and T. Ogasawara: "Piezoelectric tweezer-type end effector with force-and displacement-sensing capability", *IEEE/ASME Transactions on Mechatronics*, Vol.17, No.6, pp.1039–1048 (2012)
(51) J. Kongthon and S. Devasia: "Iterative control of piezo actuator for evaluating biomimetic, cilia-based micromixing", *IEEE/ASME Transactions on Mechatronics*, Vol.18, No.3, pp.944–953 (2013)
(52) R.J.E. Merry, D.J. Kessels, W.P.M.H. Heemels, M.J.G. van de Molengraft, and M. Steinbuch: "Delay varying repetitive control with application to a walking piezo-actuator", *Automatica*, Vol.47, No.8, pp.1737–1743 (2011)
(53) T. Uzunovic, E. Golubovic and A. Sabanovic: "Piezo LEGS Driving Principle Based on Coordinate Transformation", In the Mechatronics, IEEE/ASME

Transactions on (Volume: PP, Issue: 99), pp.1–11, DOI:10.1109/TMECH.2014.2351272



Asif Šabanović (Non-member) received the B.S. degree in electrical engineering in 1970, the M.S. and Dr. Eng. degrees in 1975 and 1979, respectively, all from the University of Sarajevo, Sarajevo, Bosnia and Herzegovina. He is Emeritus Professor at Sabanci University, Istanbul, Turkey, and International University, Sarajevo, BiH. From 1970 until 1991, he was with Energoinvest Institute for Control and Computer Sciences, Sarajevo. In 1991, he was with the Department of Electrical Engineering, University of Sarajevo. During 1975–1976, he was a Visiting Researcher with the Institute of Control Sciences, Moscow, Russia. He was a Visiting Professor with the California Institute of Technology, Pasadena, in 1984–1985, the Hitachi Chair Professor with Keio University, Yokohama, Japan, in 1991–1992, Full Professor with Yamaguchi University, Ube, Japan, in 1992–1993, Visiting Professor with the University of Maribor, Maribor, Slovenia, in 1986, 1988, and 1989, Head of Computer-Aided Design/Computer-Aided Manufacturing and Robotics Department, Tubitak—Marmara Research Centre, Istanbul, in 1993–1995, and the Head of the Engineering Department, BH Engineering and Consulting, Istanbul, in 1995–1999. His research interests include control systems, motion control systems, robotics, mechatronics, and power electronics.