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Challenges and Perspectives in Control of Ionic Polymer-Metal Composite (IPMC) Actuators: A Survey

ALVO AABLOO[1], (Member, IEEE), JURI BELIKOV[2], (Senior Member, IEEE), VADIM KAPARIN[2], AND ÜLLE KOTTA[2]

[1]Intelligent Materials and Systems Laboratory, Institute of Technology, University of Tartu, 50411 Tartu, Estonia
[2]Department of Software Science, Tallinn University of Technology, 12618 Tallinn, Estonia

Corresponding author: Vadim Kaparin (vadim.kaparin@ttu.ee)

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ABSTRACT Ionic polymer-metal composites (IPMC) are electroactive polymers expected to be used as soft actuators in various practical areas like robotics, biomedicine and micro manipulation systems. Though IPMC actuators have many advantages (lightweight, noiseless operation, low operating voltage, possibility of miniaturization), some of their inherent properties (back-relaxation, hysteresis, high sensitivity to ambient conditions, aging) make their precise and reliable control a challenging task. This paper presents a survey of control methods for IPMC actuators. A systematic overview of the techniques, addressing the main challenges in IPMC control, is provided.

INDEX TERMS Control methods, electroactive polymer (EAP), ionic polymer-metal composite (IPMC), smart material, soft actuator.

I. INTRODUCTION

Ionic electroactive polymers (IEAPs) are a type of smart materials that have the ability to change their shape while an external power source is applied. Moreover, they have sensing ability. The reason of these properties is re-arrangement of ions inside the material in response to electric potential or mechanical stress [1]. In short, these materials are electrochemomechanical transducers. The actuators made of IEAP materials have several beneficial features such as high compliance, lightweight, large strain, low voltage, biocompatibility, high force to weight ratio, and ability to operate in an aqueous environment as well as in open air [2]. The materials can be fabricated in different shapes and can be scaled down to microscopic sizes [3]. Due to these advantages, IEAP actuators are considered promising in the field of soft robotic systems. Some of IEAP materials are biocompatible and to some extent medically safe [4]. Therefore, precise medical devices with higher dexterity and soft catheters with built-in actuation are also considered as applications with high potential [5]–[7]. For instance, in [8] IEAP actuators are suggested to be applied within the human eye for focusing an artificial intra-ocular lens, usually implanted as a treatment of cataracts. The authors of [9] developed a wirelessly controlled drug delivery device, intended to release a specific drug quantity to particular body tissues and thereby lower side effects. Among the variety of other IEAP-based potential applications one can mention robotic surgical scalpels [10], [11], a wirelessly powered soft microgripper [12], a compact valveless pump [13], a linear actuator for biped walking robot [14]–[16], underwater biomimetic microrobots [17], a two-link manipulator [18], three-dimensional omnidirectional elastic tweezers [19], and Braille displays [20].

The design of soft robots and soft manipulators are often inspired by biological systems, which also are covered by soft materials or are actuated by electroactive materials. Soft robots have several advantages compared with conventional ones. Among the advantages are intrinsic safety for human-machine interactions, adaptability for medical and wearable technologies, simplicity of the gripping systems design [21].

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However, to use the next generation of soft robots, they should be equipped with reasonable low-cost, low-power-consumption control systems. There are dozens of control-oriented system models, based on physics [22], [23] or electromechanics [24]. However, they have several drawbacks like need for extensive computational power or need for hard-to-measure physical parameters. Also, all of these models do not take into account the aging of actuators.

The objective of this survey is to review how various control methods are used to overcome various challenges, arising in operation of IEAP actuators. Particularly, the survey is focused on ionic polymer-metal composites (IPMC). Section II portrays the variety of methods used for IPMC control and summarizes the reported results. Section III lists the main difficulties in IPMC control and approaches to address them. Note that this review is control-oriented. More general review of IPMC actuators can be found in [25].

II. CONTROL METHODS

The objective of this section is to give an overview of different methods for IPMC control and discuss their pros and cons regarding various control tasks.

A. PID CONTROL

In the case of a proportional-integral-derivative (PID) controller the control signal $u(t)$ is generated according to the following rule

$$u(t) = K_p e(t) + K_i \int e(t)\mathrm{d}t + K_d \frac{\mathrm{d}}{\mathrm{d}t} e(t),$$

where $e(t)$ is the difference between the desired and measured variables to-be-controlled (outputs) of the system. The non-negative coefficients K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. In order to achieve the optimal performance of a control system, suitable values of K_p, K_i, and K_d should be found. Simplicity is the main advantage of the PID controller. However, it requires the measurements of the real output as a feedback in order to compare it with the desired output. The inevitable need for feedback can be disadvantage, since in practice it is not always possible to use sensors for output measurements. Moreover, PID controller, tuned by conventional methods, is not robust to time-varying properties, which IPMC actuators possess.

Both [26] and [27] employed PID controllers to control the tip displacement of IPMC actuators. In [26] the underwater operation of IPMC actuator was considered. The authors designed a PID controller for a simple identified transfer function, which does not take into account hysteresis or other nonlinearities of IPMC. The gains of the PID controller were obtained via trial and error, concerning certain control objectives. The experiments demonstrated the ability of the actuator to track square and sinusoidal signals (each with amplitude of 0.05 mm and two frequencies of 0.01 and 0.02 Hz) during at least 350 seconds and 0.05 mm step signal during at least 25 seconds. The authors of [27] described the response of the IPMC actuator in a dry environment by means of a probabilistic model along with Bouc-Wen hysteresis model. Then they used a sampling-based learning algorithm with polynomial complexity to obtain proper values of PID gains, maintaining repeatability and robustness for a certain operating range. Simulation and experimental results showed that the proposed control scheme is robust to sample-dependent uncertainty and hysteretic behavior, unlike the PID controller designed for a nominal model only. During the experiments the IPMC strip accurately kept the desired displacement (up to 4 mm) during at least 40 seconds and tracked a sinusoidal command (with amplitude of 2 mm) within at least 70 seconds.

In [28]–[30] the PI controller was used to track the curvature of an IPMC actuator. In both [28] and [29] the tracking PI controller supplemented the operator-based robust right coprime factorization method, intended to stabilize the nonlinear system with uncertainties and input constraints (as well as hysteresis in [28]). In [30] the robust stable control system of IPMC from [28], [29] was identified as an equivalent transfer function. Then, using the obtained transfer function, the authors applied a multi-objective particle swarm algorithm to find the optimal gains K_p, K_i of the PI controller.

The application of fractional-order PID controllers to fractional-order models of IPMC was reported in [31] and [32]. Fractional-order models can describe more accurately memory-like characteristics of the IPMC material and fractional-order control methods are more effective than their conventional integer-order counterparts.

Another variation of the PI controller, the so-called proportional-integral-plus (PIP) controller, was utilized for IPMC control in [33]. The suggested controller was combined with two additional terms: an adaptive term for precise online identification of the system parameters, and an optimal term for online tuning the controller gains. The adaptive term was realized by means of the recursive least square method with Kalman filter, whereas the optimal term was represented by a linear quadratic regulator. This control scheme showed superior results in comparison with a digital PID controller and other opened-loop techniques applied to the same system.

In [34] the PID controller was utilized for tracking the bending angle of the IPMC actuator, which was specially designed and fabricated for a disposable active cardiac catheter. The authors of [10] applied the PI controller (tuned using an experimental iteration scheme) to stabilize the cutting force of a 1-DOF (degree of freedom) robotic surgical devise actuated by IPMC.

B. INVERSION-BASED CONTROL

Inversion-based control implies that the inverse of a model serves as a controller. Such a controller is able to work in both open and closed loops. The first option is attractive for a sensor-less control. However, in this case modeling uncertainties are not compensated by feedback. Consequently, a very accurate model is necessary.

In [35] the direct inverse of the third-order transfer function was accompanied by the Butterworth low-pass filters to control the displacement of the IPMC actuator in open loop. Then, for the sake of comparison, the PI feedback controller was added to compensate the modeling uncertainties and back-relaxation. Experimental results showed that the sensor-less inversion-based control is good for higher frequencies (such as 0.1 and 1 Hz) of the reference input signal. However, for lower frequencies (such as step response), uncompensated open-loop control can demonstrate good results only for a short period of time at the beginning of experiments, accumulating the error over the long time periods. As a result, the authors conclude that the sensor-less control of IPMC actuators is limited in applications where precise control is required. The similar approach for tracking the force of the IPMC actuator was employed in [36]. The results of both force and displacement tracking lead to similar conclusions regarding the applicability of the inversion-based sensor-less control.

The authors of [37] applied the inversion-based open-loop control to a temperature-dependent model of an IPMC actuator. More precisely, the model was identified as a transfer function of a third-order system, whose zeros and poles are quadratic polynomial functions of the temperature. Such approach allows one to control the IPMC actuator under variations of ambient temperature using a single model for the entire range of temperature. Of course, in this case an auxiliary temperature sensor is necessary. The challenge of this method is that the obtained transfer function is non-minimum phase and, as a consequence, its inverse is unstable. In order to overcome this problem, the authors of [37] applied a stable but noncausal inversion algorithm, which requires the knowledge of the desired trajectories in advance.

C. OPTIMAL CONTROL

The linear quadratic regulator (LQR) was used in [38] to eliminate the large overshoot and reduce the settling time of the IPMC actuator response to a step change in the applied voltage. In order to use LQR method, the authors of [38] developed a state space model (without any physical meaning of the states) of the IPMC actuator from an identified input-output transfer function and then designed a linear observer to estimate the states. Experiments on two IPMC actuators of different lengths demonstrated that LQR-based feedback control significantly decreases the overshoot and settling time of the response to a step change of the applied voltage.

In [39] the model-based H_∞ controller was implemented for tracking control of the IPMC tip displacement. Such controller was chosen to ensure stability in the presence of uncertainty, attenuate the effect of sensing noise, and minimize the control effort. The tracking performance of H_∞ controller was compared with that of PI controller, implemented together with a low-pass filter. Simulation and experimental results showed that the tracking error under H_∞ control is about half as much as the error under PI control. Moreover, H_∞ controller required lower control effort than its PI counterpart.

In [15] the optimal feedback (based on the Hammerstein model) was used to control the position of a linear actuator, driven by several IPMC strips. The authors of [40] applied the LQR with an observer to control a three-finger IPMC gripper.

D. ADAPTIVE CONTROL

The IPMC material is an electrochemical sensor, and consequently, its behavior is highly dependent on environmental conditions (relative humidity, temperature, pH), which, in practice, may change unpredictably. Therefore, the controller, able to adapt to such variations, is extremely valuable.

In [41], [42] the model reference adaptive control (MRAC) was implemented for the closed-loop tracking of the IPMC tip displacement. In [41] a reference model was identified and validated, using the experimental data. The performance of the controller was optimized by means of the genetic algorithm. Simulations showed the high correlation between the desired and simulated displacement. Moreover, the root mean square of the tracking error signal was less than 30%. In [42] the Prandtl-Ishlinskii operator was included into the reference model to describe the hysteresis of IPMC.

An adaptive inverse controller was designed in [43] to compensate for the creep and hysteresis of the IPMC actuator. The advantage of this control method is the operation in an open-loop configuration. Using Prandtl-Ishlinskii hysteresis model and basic creep operators, the authors of [43] developed the hybrid model of IPMC dynamics and employed its inverse as a controller for the adaptive inverse control. In the proposed control scheme the parameters of the hysteresis model and its inverse were updated online by means of the least mean square algorithm.

The paper [44] employs the adaptive integral periodic output feedback control method to regulate the output force of IPMC strips with creep characteristics. The adaptive part of the control was realized via the fast recursive least squares method, updating the model parameters online. The applied method was compared experimentally with periodic output feedback and integral periodic output feedback control schemes and showed the best result.

An adaptive method called iterative feedback tuning (IFT) was applied in [45] to optimize the positional control of an IPMC-actuated rotary joint. The main advantage of this method is that it does not require a model of the system. Moreover, it is essentially an automatic algorithm, such that the need for manual tuning is minimal. Simulations and experiments in [45] demonstrated, that iterative feedback tuning is able to significantly improve the performance of the PI controller.

E. REPETITIVE CONTROL

A number of IPMC applications are based on periodic oscillatory motions of the actuator. The examples of such applications are active endoscopes [46], caudal fins of robotic fishes [47], and pumps [13]. Repetitive control (RC) is a simple learning-type control method, which was developed specifically to track periodic reference trajectories and reject periodic disturbances. The method is distinguished by its high precision, simple implementation and little performance dependency on system parameters [48]. The basis of the RC is an internal model that generates a signal with the same period as that of the reference one in the closed loop. Unlike the PID controller, the RC method does not require the knowledge of the exact transfer function of a plant and precise tuning. Moreover, it can reduce the error on each operating cycle [49]–[51]. Most analysis and design of the RC are performed in the frequency-domain, which can be a limitation, since in this case a linear model is required to design the RC for a nonlinear system [48], [52].

In [53]–[55] the RC was applied to an experimental IPMC actuator for tracking sine and triangle reference trajectories at 0.5, 1.0, 1.5, and 2.0 Hz. The tracking results were compared with those of a discrete-time PID controller. The experiments showed that the RC significantly reduces the measured tracking error in comparison with the PID controller. For example, [53], [55] report that at 0.5 Hz, the maximum error with the RC is 3.4%, over 55% lower compared to the PID controller. The results of [54] demonstrated over 50% reduction of the tracking error, from 9.5% for PID controller to 4.5% for the RC method. The RC begins to take effect after the first period and, unlike the PID controller, its tracking error diminishes with each operating period, where steady state is achieved after approximately three (in [53], [55]) or six (in [54]) cycles. The paper [54] reports that for a square wave reference signal at steady state the PID controller responded with significantly higher overshoot (50.0%) than the RC (with 14.9% overshoot). The settling time for both controllers was approximately the same (200 ms).

In [13] the RC strategy was successfully applied to a compact IPMC-actuated double-chamber valveless pump. In preliminary experiments the authors compared the tracking performances of the RC and the IFT. The input reference was a ± 1 V, 0.1 Hz sine wave. For IFT the controller output signal was quite noisy compared with that of the RC. Though initially the IFT had a better performance than the RC in the first nine cycles, its static error was nearly two times of RC. The control effort of the RC was found to be lower than that of the IFT after 12th cycle due to the less oscillation. Moreover, during the experiments the RC consumed three times less memory than the IFT, which involves a lot of matrix operations, including multiplication and transpose operations, requiring considerable calculation resources. In the next two experiments the RC performance was tested on a free-standing IPMC operated 1) over a long period of time and 2) at various reference signals. The first of these experiments showed that the RC is able to track the input and keep the error in a relatively low range for at least 120 min, after which the error and control effort increased dramatically because of the dehydration of IPMC. In the second experiment eight sine wave signals with various amplitudes and frequencies were used as the reference input. On the basis of this experiment the authors conclude that the RC makes the IPMC capable to track various input references for most of the conditions except 0.5 Hz, where the IPMC has a low magnitude response and the voltage saturation prevents control effort from going higher.

F. SLIDING MODE CONTROL

The sliding mode control is a well-known method, which has the advantage of being robust to model uncertainties. The main problem of the sliding mode control is a chattering phenomenon, caused by the switching action. To overcome this problem a smooth control action is applied. Nevertheless, the application of such action requires the trade-off between tracking accuracy and robustness against uncertainties.

The sliding mode approach was used in [56] to guarantee the robust stability of the IPMC system with uncertainties and input constraints. In order to improve dynamic performance of the sliding mode controller and suppress chattering, the authors employed the exponential reaching law and a saturation function in the control law. Then the PI controller was applied to the sliding mode control based stabilizing system to track the IPMC curvature. The parameters of PI controller were optimized by the back-propagation neural network. On the basis of simulations the authors compared the proposed method with the PID controller and the right coprime factorization technique (see [28], [29]). As a result, the sliding mode controller showed the best performance, especially in the presence of disturbance.

The authors of [57] designed a nonsingular terminal sliding mode (NTSM) controller to investigate the robustness issue of IPMC tip displacement tracking under change of working conditions, presence of uncertainties and disturbances. Unlike the conventional sliding mode, the NTSM control guarantees a finite time convergence of the system states to zero. In order to verify that the proposed method is robust against uncertainties, experiments were conducted under two different working conditions: the IPMC actuator was fully immersed in water and only three-quarters of the actuator was immersed. Moreover, two different sinusoidal reference signals were used in the experiments. The ability of the controller to reject external disturbance was checked by means of an electrical shock disturbance. The experimental results demonstrated that the NTSM control is robust against variations of both working conditions and reference characteristics. Moreover, it guarantees fast convergence to steady state in a presence of an external disturbance. The performances of the NTSM and PID controllers were compared under the same experimental conditions and the results showed the superiority of the NTSM over the PID controller.

A new fractional-order sliding mode control was presented in [58] for an IPMC actuator modeled as a fractional-order system. The proposed controller is a generalization of a second-order sliding mode controller (called super-twisting algorithm) to the fractional-order one. The fractional super-twisting controller and its modified version were tested experimentally and their performance was compared with that of PI controller. Both the proposed controllers showed better results than the PI one without yielding any significant increase of the required input voltage.

In [59] the sliding mode control was verified for different shapes and sizes of IPMC. The experiments on four different IPMC samples demonstrated that the sliding mode controller is able to track both the tip displacement and force of IPMC, effectively resisting creep characteristics of different samples without the necessity to change parameters of the control systems. The authors of [59] conclude that the simple replacement of a failed IPMC actuator with a similar new one without any other adjustments of the system is possible under the sliding mode control.

The authors of [60] combined an integral and nonsingular terminal sliding modes in order to construct a new integral nonlinear sliding surface, leading to a fast convergence, accurate tracking, and the robust performance. Moreover, an adaptive switching gain was applied to estimate uncertainties. The experimental results demonstrated better performance and excellent robustness of the proposed controller in comparison with the conventional NTSM control [61].

In [62] the position tracking of the IPMC actuator was realized by means of a super-twisting sliding mode controller combined with an integral-chain differentiator as a state observer. Compared with the conventional sliding mode control, its super-twisting counterpart provides faster convergence without chattering. The integral-chain differentiator can produce continuous state estimations relying only on the position measurements. The proposed control method was experimentally verified and compered with an optimal PID controller. Unlike the PID controller, the super-twisting sliding mode control is less sensitive to external disturbances and noise of the sensor.

G. OTHER METHODS

Lead-lag compensators were used for IPMC control in [63], [64]. A lag compensator was employed to decrease the overshoot and reduce the settling time during precision microscale control of the IPMC actuator. The position resolution, maximal and minimal controlled tip displacement, and maximal speed of bending were tested experimentally.

The gain-scheduled model predictive control (MPC) algorithm was employed in [65] for position control of the IEAP actuator under varying relative humidity conditions. In order to describe the actuator dynamics, the authors developed the general multilayer neural network model, in which relative humidity magnitude was used as one of the model parameters, making the model adaptable to changing environmental conditions. The experimental results showed that the proposed method is well capable of controlling accurately the actuator under relative humidity conditions varying in the range of 10–90%.

In [66] a nonlinear controller based on the feedback linearization method was designed for IPMC actuators, described as a one-segment nonlinear circuit model, incorporating the nonlinear capacitance, the nonlinear DC resistance, and the effect of surface resistance. Simulation results demonstrated that the model-based nonlinear control performs better than the PI control in terms of tracking error, control effort, and robustness to sensing noises.

The method called an active disturbance rejection control was proposed in [67] for the precise underwater position tracking of the IPMC actuator with the internal uncertain nonlinear dynamics and external disturbances. The suggested control scheme consists of a tracking differentiator, an extended state observer for estimating an unknown term, and a nonlinear state-error feedback element. The advantage of the method is that it does not require an explicit mathematical model of the plant and has active disturbance rejection. The active disturbance rejection control demonstrated better experimental results than the traditional PID controller.

In both [68] and [18] the time-delay control was applied to IPMC actuators. The paper [68] addressed the tracking of tip displacement, whereas in [18] the force control was considered. Moreover, in [18] the time-delay control was applied to track the force of a two-link manipulator actuated by two IPMC strips. Robustness and simplicity are two advantages of the time-delay control. The method does not require the detailed model of a system, but only the knowledge of the order of system dynamics is needed. In both [68] and [18] the first-order dynamic equations were employed as models of IPMC behaviors. The design procedure of the time-delay control is straightforward, since it uses a simple and efficient time-delay estimation method, which requires only the previous values of states and control inputs in order to predict and cancel unknown dynamics of the system. Unlike the sliding mode control, the time-delay control does not have a problem of the chattering phenomenon, resulting from the switching action in the sliding mode control. The experimental results of [68] and [18] show that the time-delay control yields good transient and steady state responses. Moreover, it is exceptionally robust against the time-varying characteristics of the IPMC strip and can closely follow the desired reference signal even in repetitive experiments.

In [69] and [70] a robust controller based on the quantitative feedback theory was employed for position tracking of the IPMC actuator. The quantitative feedback theory is well suited for systems with large parameter uncertainties. In [69] the second-order transfer function served as a model in the controller design, whereas in [70] for this purpose a nonlinear electromechanical model of the IPMC was developed and then reduced to a family of the fourth-order linear uncertain transfer functions.

H. DISCUSSION

A number of various methods for IPMC control are presented in the literature. Nevertheless, non of the methods can completely capture the full complexity of IPMC dynamic behavior. On the one hand, some of the methods, like PID controller or lead-lag compensator, are very simple, but less accurate and not robust against changing operating conditions. On the other hand, the application of more advanced robust methods, like sliding mode control or adaptive control, inevitably

TABLE 1. Control methods and related models.

Control method	linear black-box model	nonlinear black-box model	nonlinear gray-box model	model-free
PID controller	[26], [27], [30]		[28], [29]	
Fractional-order PID controller	[31], [32]			
PIP controller	[33]			
Inversion-based control	[35]–[37]			
LQR	[38], [40]			
H_∞ controller	[39]			
MRAC	[41]	[42]		
Adaptive inverse controller		[43]		
Adaptive integral periodic output feedback control	[44]			
IFT				[45]
RC	[53], [54]			
Sliding mode control	[57], [59]–[62]		[56]	
Fractional-order sliding mode control	[58]			
Lead-lag compensator	[63], [64]			
MPC		[65]		
Feedback linearization based controller			[66]	
Active disturbance rejection control		[67]		
Time-delay control	[18], [68]			
Quantitative feedback theory based controller	[69], [70]			

complicates the control system. Therefore, the choice of an appropriate control method is always a trade-off between simplicity and accuracy.

Another important aspect is whether a control method is model-based or model-free, since modeling of IPMC behavior is a challenging task as well. Table 1 shows that the majority of the available methods for IPMC control rely on a model, whereas only IFT is a model-free technique. Moreover, linear empirical models were used in most cases of model-based methods. Though such models are fairly simple, they cannot accurately describe highly nonlinear behavior of IPMC. However, more accurate physics-based models require more computation power and can be too complex for real applications.

Almost all considered methods, except for inversion-based control, need feedback, which may rise sensors-related problems (discussed in Section III-E). Though feedforward methods can be used without sensors, they cannot compensate modeling uncertainties. Therefore, the model should be very accurate. Otherwise, the method will be effective only for a short period of operation due to accumulation of an uncompensated error.

Furthermore, there are methods, like RC, which are more suitable for repetitive motions of the IPMC actuator, improving the performance from one operating cycle to the next. Such technique can minimize the requirements for sensor feedback, relying only on periodic measurements of cumulative performance (like distance traveled by a walking robot or fluid pumped) rather than on continuous monitoring of a system output (like actuator displacement) [71]. Note, however, that non-strictly repetitive factors (such as iteration-varying reference trajectory, system parameters or disturbances) can limit the application of the RC.

III. CHALLENGES AND SOLUTIONS IN IPMC CONTROL

Inherent properties of IPMC material and its anticipated applications pose a number of challenges for precise and reliable control. The main challenges and suggested solutions are discussed in this section and summarized in Table 2.

A. BACK-RELAXATION

The back-relaxation (also called stress-relaxation, reverse relaxation, and creep property) is an IPMC inherent phenomenon, characterized by the inability to maintain a stable value of the output under the fixed value of the input signal. For instance, under sustained DC voltage (step input signal) the material first bends in a given direction (see Fig. 1). However, after reaching a certain maximum deflection it slowly relaxes towards its initial position without maintaining a steady state. If now to remove the control signal, the actuator continues to move back, usually overshooting its initial position [85], [86]. The blocking-force of IPMC actuators demonstrates similar behavior. As a result, the back-relaxation interferes control precision, limits the range of control frequencies and duration of effective operation. In [86] it was shown that the effect of the back-relaxation (along with forward displacement or force) is extremely sensitive to the level of humidity: the higher the humidity, the stronger the effect. Besides efforts to diminish/eliminate the back-relaxation at the level of chemical analysis, material engineering, and fabrication [87]–[96], there exist a number of attempts to conquer it by means of modeling and control methods, discussed more thoroughly below.

1) MODELING

In [74] a simple linear four-parameter model was developed to express the relaxation phenomenon. The authors

TABLE 2. Challenges and methods in IPMC control.

		CHALLENGES IN IPMC CONTROL							
		simplicity	back-relaxation	hysteresis	intra-sample variations	inter-sample variations	scalability	sensitivity to ambient conditions	sensor-less control
CONTROL METHODS	PID controller	[10], [26]–[30], [34]	[34]	[34]					
	Lead-lag compensator		[64]		[64]				
	Inversion-based control							[37]	[32], [35]–[37], [43], [72]
	MRAC			[42]				[41]	
	Adaptive inverse controller		[43]	[43]					
	Adaptive integral periodic output feedback control		[44], [73]						
	IFT				[45]			[45]	
	Sliding mode control		[59]			[59]	[59]		
	MPC							[65]	
	Active disturbance rejection control				[67]				
	Time-delay control	[18], [68]			[18], [68]				
MODELING	Four-parameter model	[74]	[74]						
	Physics-based models		[75]–[77]	[75]			[75], [78], [79]	[80]	
	Creep operators		[43], [44], [73]						
	Hysteretic models			[27], [28], [42], [43], [81]–[83]					
	Fractional-order model	[84]					[84]		

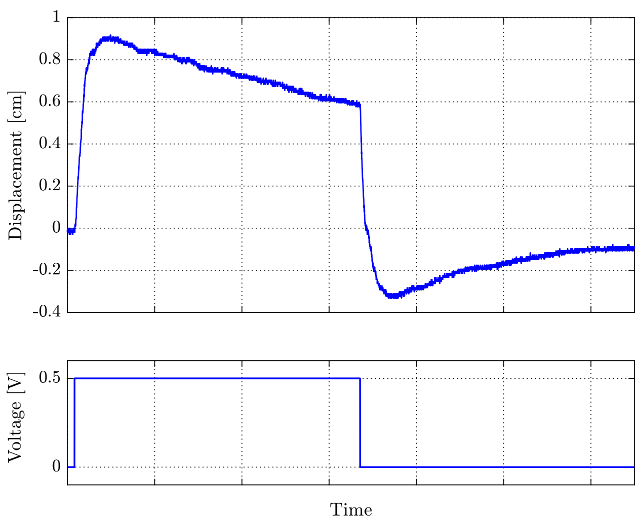


FIGURE 1. Response of IPMC to step voltage input.

of [75] designed an electromechanical model to fully capture the nonlinear response (including the back-relaxation) of an IPMC at low frequencies of the control signal. The model consists of three parts: a nonlinear equivalent electrical circuit, predicting the current drawn; an electromechanical coupling term; a segmented mechanical beam model, which includes an electrically induced torque for the polymer. Another electromechanical model was proposed in [77] and further developed in [76]. In this model an equivalent electrical circuit was used to predict the transient electrical charge, which then was proportionally coupled with an appropriate adaptation of a viscoelastic model, properly composed of such primitives as a spring and a damper, imitating the back-relaxation. In [43], [44], [73], the back-relaxation is modeled as a sum of basic linear creep operators. The more operators used, the higher the accuracy one can achieve.

2) CONTROL METHODS

Usually the back-relaxation is compensated by means of feedback-based control techniques, such as the PID controller [34], digital lead-lag compensators [64], periodic output feedback control [44], [73] and sliding mode control [59]. The drawback of traditional feedback-based control methods is constant increase of the input voltage for compensation of the back-relaxation. At the same time higher voltage may irrevocably damage the actuator, so the increase of the voltage must be limited, which, as a consequence, restricts the compensation of the back-relaxation. The results on application of a feedforward control method against the back-relaxation were reported in [43], where an adaptive inverse

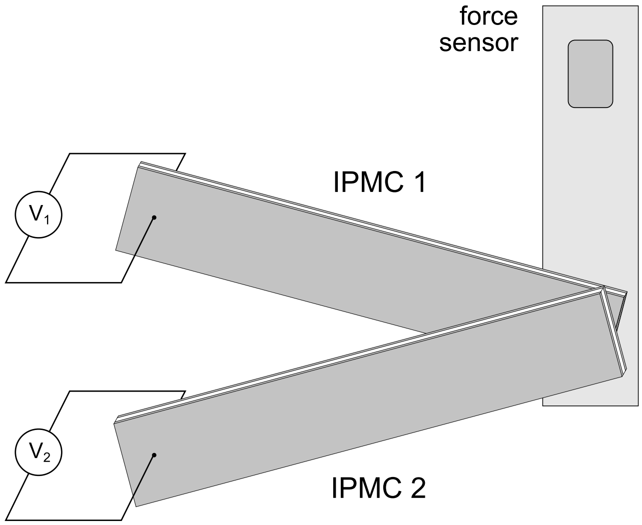
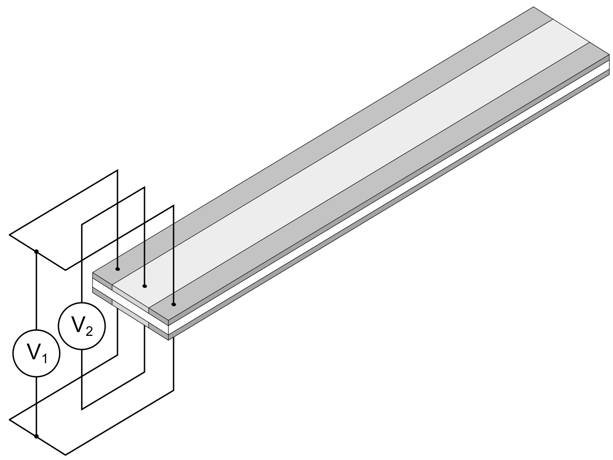
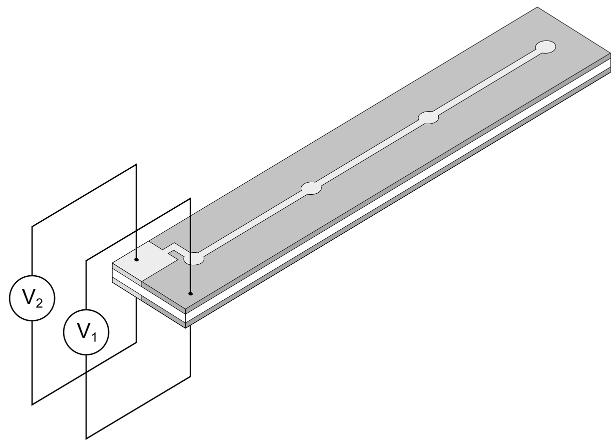


FIGURE 2. Cooperative control of two IPMCs [97].



(a) Pattern proposed in [85].



(b) Pattern proposed in [99].

FIGURE 3. IPMCs with two control regions on patterned electrodes.

controller was used. Fundamentally different approaches are suggested in [85], [97]–[99]. The authors of [97] propose to use cooperatively two (or more) IPMCs, whose main control signals are supplemented with small anti-phase fluctuating components. The idea is to orient the actuators such that their tips are layered one above the other and apply the forces to the same point (see Fig. 2). Fluctuating signals apparently affect the behavior of an IPMC on a molecular level and reduce the effect of the stress-relaxation. The anti-phase fluctuations of several IPMCs are intended to cancel each other in the total output force. In [85], [98], [99] IPMCs with patterned electrodes are employed for mitigating the back-relaxation. In [85], [98] it is suggested to divide the electrodes into several parts (three in the referred works) along the entire length of the actuator and combine these parts into two sectors, such that each sector can be activated separately (see Fig. 3a). The strategy is to activate one of the sectors for the main motion of the actuator and another for compensation of the back-relaxation, when it appears. Though in the experiments an integrated feedforward and feedback controllers were employed together with the linear model from [74], more advanced control methods and accurate nonlinear models can be used in the proposed control scheme. The paper [99] is in a sense a combination of some ideas from [97] and [85], however with conceptual differences. Like in [85], patterned electrodes are used, but the shape of the pattern is different: electrodes are divided into two isolated regions, one of which is much smaller than the other (see Fig. 3b). Like in [97], the authors of [99] use an oscillating signal to affect the IPMC on a molecular level and reduce the effect of the back-relaxation; however, they use the different signal (Gaussian noise) and apply it to the smaller regions of the electrodes at the stage of the back-relaxation, such that the oscillating signal is totally separated from the main driving signal (applied to the bigger regions). The advantages of the method from [99] are that feedback acquisition is not required and it is reliable even for large bending displacements.

B. HYSTERESIS

The hysteresis properties are described by multivalued nonlinear functions. For instance, several values of the IPMC tip displacement may correspond to the same input voltage (see Fig. 4). This dynamical feature characterizes the behavior of many smart materials, including IPMC. Under the hysteretic nonlinearities the system usually exhibits undesirable oscillations and instability [28], which limits the operating speed and precision [42]. In order to overcome these disadvantages, the mathematical model of IPMC should be able to adequately describe the hysteretic behavior. Typically, for that purpose identification of various hysteretic models is used in the literature. Among such models are the Preisach operator [81], Prandtl-Ishlinskii hysteresis models [28], [42], [43], [82], [83], and Bouc-Wen hysteresis model [27]. In [100] the least squares support vector machine nonlinear autoregressive model was developed to eliminate the effect of the hysteresis. Moreover, an inverse controller was combined with the PID feedback control to compensate the hysteretic characteristics. Apart from identification based approach is the physics-based electromechanical model from [75], designed to account, besides other nonlinearities, hysteresis effects of IPMC.

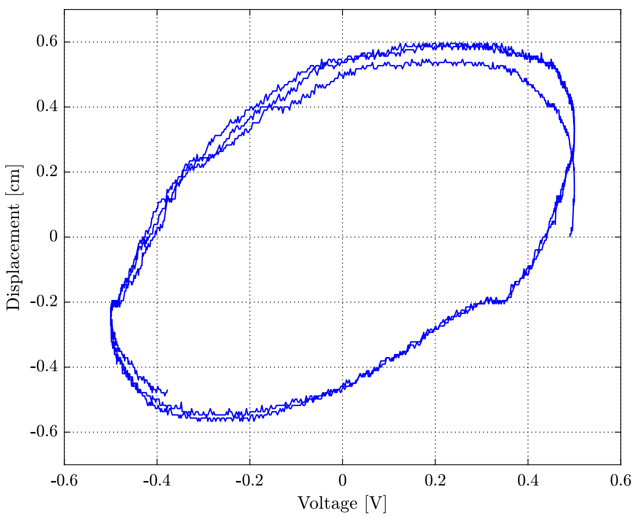


FIGURE 4. Relation between input voltage and corresponding displacement of IPMC.

C. GEOMETRIC SCALABILITY

The IPMC material allows one to get actuators of different shapes and sizes to be used in a wide range of applications. However, the shape and size of IPMC actuators highly affect their dynamics and usually one has to use different models to describe the dynamics of actuators, which differ in shape and size. Therefore, it is extremely useful to develop a geometrically scalable model, i.e., a single model which can adequately describe the behaviors of different actuators, using their geometric parameters. The progress in this direction is described below.

In [78] Bonomo *et al.* presented a gray box model, consisting of two parts. A nonlinear electrical part describes the transduction of the applied voltage into the absorbed current and is modeled as an equivalent electric circuit, whereas an electromechanical part converts the absorbed current into the produced tip deflection or the blocking force. Since the parameters of the model have physical interpretation, they can be scaled as functions of the geometric size of the IPMC membrane. In [79] Martinez and Lumia developed a distributed force model, which is able to simulate the force output of an IPMC actuator of arbitrary shape and size at any point on its surface. The model consists of several interlinked sub-models, referring to a particular physical phenomenon: an electrical model for arbitrary shapes, an ion migration model, and a force model. The model showed close correspondence between the experimental and simulated results. Another geometrically scalable model is the model from [75], mentioned in previous sections. Establishing an accurate dynamic relationship between the force and displacement, this model is able to predict the complete actuation response of the IPMC transducer, unlike the model from [78], where either the free displacement or blocking force can be expressed. In [84], [101] Caponetto *et al.* modeled an IPMC as a fractional-order transfer function, parameterized by the length of the membrane. Though the model takes into account only the length, it has the advantage of simplicity.

D. INTRA-SAMPLE, INTER-SAMPLE AND AMBIENT VARIATIONS

In general, the dynamic behavior of an IPMC is characterized by different variations, which complicate the modeling and control. Here we divide the main types of variations into three categories.

1) INTRA-SAMPLE VARIATIONS

Intra-sample variations are changes in the dynamic behavior of a single IPMC sample under several activations with the same control inputs and external conditions. Such phenomenon, also referred to as IPMC aging and non-repeatability of IPMC responses, is caused by complicated electrochemical reactions in the ionic-polymer material. In [64] a lead-lag compensator was used in a closed-loop mode to overcome the non-repeatability of IPMC responses. In [67] the internal time-varying characteristics of an IPMC were incorporated into the model as an unknown nonlinear function, and then the active disturbance rejection control was employed to compensate nonlinear model uncertainties. Both [68] and [18] claim that the time-delay control method is robust against the time-varying characteristics of IPMC and can accurately track the desired reference signal even upon the repeated actuation.

2) INTER-SAMPLE VARIATIONS

Inter-sample variations are differences in the dynamic behaviors of different but identical in size and composition IPMC samples. Even the samples from the same batch can behave slightly differently from one another. For this reason, as a rule, application of a new IPMC sample requires changing the parameters of the model and controller. However, [59] reports that the sliding mode control method allows one to replace IPMC samples without any changes of the controller parameters.

3) AMBIENT VARIATIONS

Variations based on ambient conditions are changes in the dynamic behavior of an IPMC material under varying temperature, relative humidity, pH [102]–[105]. In [80] Caponetto *et al.* developed a physics-based model, which takes into account the influence of the relative humidity on IPMC actuators. The model consists of electrical, chemical, thermal, and mechanical sub-models interacting through coupling terms. In order to make the model sensitive to moisture variations, several of its parameters were optimized for four values of relative humidity: 40%, 60%, 80%, and 100%. In [65] the behavior of an IPMC actuator was modeled as the general multilayer neural network tuned by the Levenberg-Marquardt back-propagation algorithm, such that the magnitude of relative humidity was incorporated as one of the model parameters. The model together with the gain-scheduled model predictive controller was experimentally verified at a humidity level varying from 10% to 90%. In [37] IPMC behavior is modeled as a transfer function, whose zeros and poles depend on ambient temperature. Then, using temperature measurement, the model is inverted at the current temperature value to be used in open-loop control. The authors of [106] incorporated the humidity-dependence of the IPMC actuator into the physics-based model from [107]. Moreover, they applied an adaptive observer to estimate unknown moisture content through a varying IPMC resistance, such that a humidity sensor is not required. Then a back-stepping control algorithm was developed for long-term continuous operation in the air.

E. ISSUE OF SENSING

The most common sensors used for feedback control of IPMC actuators (at least in laboratory environments) are lasers, charge-coupled device cameras, and force sensors. Laser sensors are frequently employed to measure the tip displacement, whereas cameras can be engaged in estimation of IPMC curvature profile. Both laser and camera do not come into physical contact with the actuator. The advantages of lasers are broad sensing range and high resolution. Moreover, laser beam can penetrate transparent materials (water and some plastics), which makes it a good tool for underwater experiments. However, the reflective surface of the IPMC material sometimes may corrupt the measurement of the distance between the laser and the material. Another disadvantage is that, in general, laser sensors are not suitable for detection of large bending deformations. Since the IPMC tip moves along a circular path, it may go outside the laser beam under large bending deformations. Unlike lasers and cameras, force sensors physically contact IPMC actuators. The force sensor blocks the motion of the IPMC tip, however, the middle part of the actuator may continue to deform under control voltage, which may distort the measurements of the force. The common disadvantage of traditional lasers, cameras, and force sensors is that they are too bulky to be used in tiny devices. Efforts to overcome the problems of traditional sensors can be divided into three directions, described below.

1) SENSOR-LESS METHODS

The *sensor-less control* means the absence of any sensors, measuring the output of the system (i.e., tip displacement, curvature, or force). In this case the methods of feedforward control or indirect estimation are employed. The feedforward methods include the inversion-based control, applied to IPMC actuators in [32], [35]–[37], [43], [72]. The authors of [108] offered to estimate the IPMC position by means of an observer, developed for the nonlinear model from [107]. This approach requires the knowledge of the current, which can be calculated by measuring the voltage of a small resistor, connected to the IPMC actuator in series. In [109], [110] neural network based black-box models of IPMC are suggested to be used as ‘‘virtual sensors’’, computing tip displacement. The main disadvantage of sensor-less control is the need for a very accurate model, which is difficult to achieve for IPMC actuators.

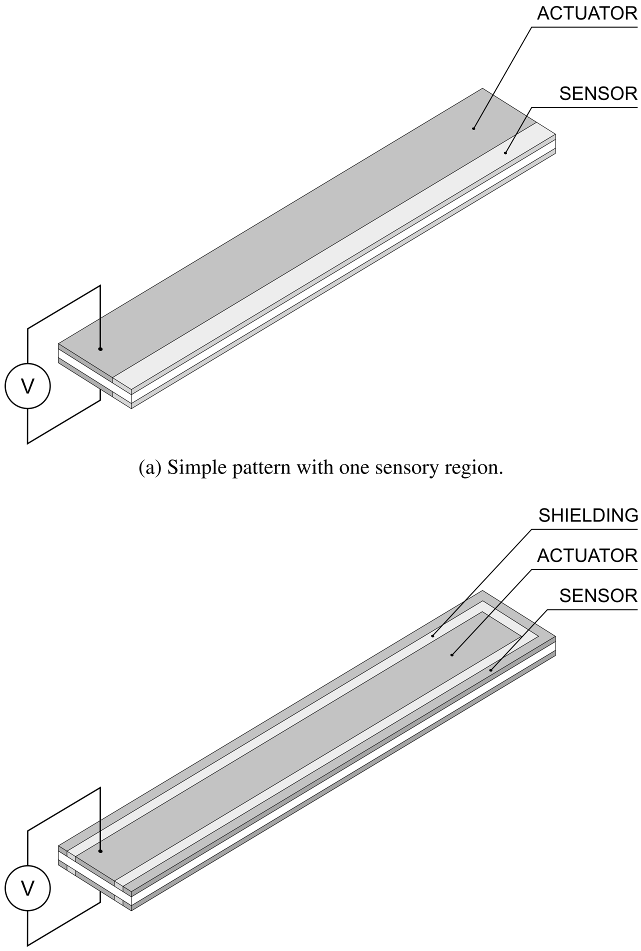
2) SELF-SENSING METHODS

Self-sensing[1] methods suggest to use the sensory capabilities of the IPMC actuator itself, measuring changes in its internal electrical parameter(s) to deduce the actual output. Two most common self-sensing techniques utilize the surface resistance of the IPMC metal layers [111], [112] and the conversion of mechanical deformation to electrical signals [113], [114]. Furthermore, the authors of [115], [116] propose to use the charged voltage inside the IPMC, which correlates with its curvature. In order to distinguish the charged and control voltages, it is suggested to measure the charged voltage during an instantaneous open-state status made by means of an analogue switch. In [72] the total charge of the dehydrated IPMC was used for self-sensing feedback control at the extremely low absolute humidity of the environment, in which the relationship between the bending curvature and total charge becomes linear. Another self-sensing technique, called the high-frequency resistance sensor, was presented in [117]. The method allows one to detect the bending of the actuator by measuring the resistance across the IPMC at a sufficiently high frequency, which makes the voltage-current dependency to show a linear behavior and follow Ohm's law. Since self-sensing assumes *simultaneous* employment of the IPMC as an actuator and a sensor, one of the major issues is separation of driving and sensing signals to avoid undesired feedthrough or cross-talk effects. In order to overcome this difficulty one may apply patterned electrode layers, such that the electrodes are divided into electrically isolated but physically connected sections, one of which is used purely as a sensor and the other as an actuator (see Fig. 5). Moreover, as shown in Fig. 5b, an additional section between the sensor and actuator can be used as a shielding to overcome the cross-talk effect. More information about self-sensing methods can be found in the review paper [118].

3) INTEGRATED SENSING

The *integrated sensing* aims to use alternative sensors, suitable for miniaturization and embedding into a device. For instance, in [10] instead of *directly* measuring the force, a simple strain gauge is used to measure the deflection of a cantilever beam, actuated by the IPMC. Then the force can be calculated from the measured deflection. The strain gauge is cheap, small scale, and, unlike force sensors, does not block the IPMC displacement. In [54] two strain gauges, bounded to the surface electrode of the IPMC, are utilized for monitoring the displacement of the actuator. Besides, the authors of [119] developed both bending and force integrated sensors based on polyvinylidene fluoride (PVDF) films. The bending sensor consists of two thin PVDF films, bonded in opposite polar directions to both sides of the IPMC actuator with insulating layers in-between, whereas the force

[1]Note that the notions ‘‘sensor-less’’ and ‘‘self-sensing’’ are often used interchangeably in the literature. However, here we clearly distinguish them and use for conceptually different approaches.



(a) Simple pattern with one sensory region.

(b) Pattern with a sensory region and shielding, connected to the ground.

FIGURE 5. Self-sensing IPMCs with patterned electrodes.

sensor represents a thin polyester beam sandwiched by two PVDF films and attached at the end of the IPMC actuator. Another integrated sensing approach suggests to use the sensing signal from a complementary IPMC sample(s), coupled with the IPMC actuator in a side-by-side or multilayer configuration [11], [120]–[122]. A contactless inductive coil sensor was utilized in [13] to detect the distance to the IPMC tip in a compact double-chamber valveless pump.

IV. DISCUSSION AND CONCLUSION

The overview demonstrates, that nowadays a variety of methods for IPMC control can be found in the literature. Nevertheless, none of the suggested methods is universal, meaning that if an approach proved to be good for one task, it may not be so for another. Consequently, the choice of an appropriate control method is frequently determined by specific purposes or potential applications. It matters, whether the IPMC will be used in constant or changing working conditions, what range of output response (displacement/force/curvature) is required, whether the accuracy or simplicity is a higher priority, whether it is possible to use a sensor for feedback or not. It is also necessary to take into account the types of motions that an IPMC actuator is intended to perform in a particular device. For periodic oscillatory motions one may choose simpler control methods like repetitive control, whereas the precise maintaining of a certain position or level of force can require more advanced adaptive methods. Furthermore, the choice of an IPMC model deserves attention. The majority of the described control methods can handle fairly simple black-box models. However, in this case the accuracy may suffer and a sensory measurements are required to compensate model uncertainties. On the other hand, detailed gray or white box models can be too complex to be used in a real device and mainly they remain the objects of laboratory research. Moreover, it seems that a single control method cannot overcome such difficulties as back-relaxation, hysteresis, dynamic variations, etc., but rather a combination of various methods of modeling, control, and material fabrication is required. Finally, there is almost no comparative analysis of the effectiveness of various methods in the literature. Mainly, a more advanced method is compared with the PID controller, but the comparison of different advanced methods is practically absent.

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ALVO AABLOO (Member, IEEE) received the Ph.D. degree in solid state physics from the University of Tartu, in 1994. From 1995 to 1996, he was a Postdoctoral Researcher with the Ångström Laboratory, Uppsala University. Since 2007, he has been a Professor of polymer materials technology with the Institute of Technology, University of Tartu. His current research interests include atomistic and multiscale modeling of polymer electrolytes and their inter faces, radiation damage studies, electromechanically active polymer transducers, and their applications in robotics and micro devices.

JURI BELIKOV (Senior Member, IEEE) received the Ph.D. degree in computer and systems engineering from the Tallinn University of Technology, in 2012. From 2015 to 2017, he was a Postdoctoral Fellow with the Faculty of Mechanical Engineering and the Andrew and Erna Viterbi Faculty of Electrical Engineering, Technion—Israel Institute of Technology, Haifa, Israel. He is currently an Assistant Professor with the Department of Software Science, Tallinn University of Technology, Tallinn, Estonia. His main research interests include edge of nonlinear control theory and power systems.

VADIM KAPARIN received the Ph.D. degree in computer and systems engineering from the Tallinn University of Technology, in 2013. He is currently a Research Scientist with the Department of Software Science, Tallinn University of Technology. His main research interests include domain of nonlinear control system theory and both for discrete- and continuous-time cases as well as for systems on time scales.

ÜLLE KOTTA received the Ph.D. degree from the Estonian Academy of Sciences, in 1980, and the D.Sc. degree from the Russian Academy of Sciences, in 1993. She is currently a Lead Research Scientist with the Tallinn University of Technology. She is the author of a research monograph and the (co)author of more than 200 journal articles. She has supervised numerous Ph.D. students. Her research interest includes nonlinear control theory and her group is a part of the Estonian Center of Excellence (EXCITE). In 1996 and 2018, she was awarded the Estonian Science Award.