

Locomotion Principles for Microrobots Based on Vibrations

F. Becker, V. Lysenko, V.T. Minchenya, O. Kunze
and K. Zimmermann

Abstract Microrobotics is a growing field with great advances in recent years. New applications in the fields of medicine, biology, manufacturing and maintenance technologies are developed. They require mobile systems with enhanced motion abilities. The present paper concerns principles of terrestrial locomotion for vibration-driven microrobots. Such systems are characterized by an internal periodic excitation, which is transformed to a directed motion due to asymmetric system properties. An extensive overview on the state of the art shows the great potential of the vibration-driven locomotion for miniaturized applications in technics. To perform a controllable two-dimensional locomotion with only one actuator, it is needed to overcome limits of rigid body systems. The proposed approach uses the frequency-dependent vibration behavior of elastic systems, like beams and plates. Experimental investigations are supported by finite element method. It is shown that the two-dimensional locomotion on a flat and solid ground can be controlled by only one actuator using the resonance characteristics of elastic systems.

Keywords Locomotion · Mobile robotics · Microrobot · Vibration · Resonance

F. Becker (✉) · O. Kunze · K. Zimmermann
Department of Mechanical Engineering, Technical Mechanics Group,
Technische Universität Ilmenau, Ilmenau, Germany
e-mail: felix.becker@tu-ilmenau.de

O. Kunze
e-mail: oliver.kunze@tu-ilmenau.de

K. Zimmermann
e-mail: klaus.zimmermann@tu-ilmenau.de

V. Lysenko · V.T. Minchenya
Department of Construction and Production of Instruments,
Belarusian National Technical University, Minsk, Belarus
e-mail: victor_lysenko@mail.ru

V.T. Minchenya
e-mail: vlad_minch@mail.ru

1 Introduction

A mobile robot can perform locomotion and, due to it, has an increased working space. It is characterized amongst others by its size and mass. The term microrobot has been defined “to include the robotic manipulation of objects with characteristic dimensions in the millimeter to micrometer range (micromanipulation), as well as the design and fabrication of robotic agents in a similar size range (microrobots)” (Abbott et al. 2007). In the literature, the use of the term is not consistent. Robots with physical dimensions in the range of millimeters or centimeters are called mini, micro, or miniaturized. The complexities of fabrication and application of a mechatronic system strongly increase by decreasing the size. That is why the volume of a robot should be chosen as a characteristic physical parameter. Following the volume dependent classification proposed by Caprari (2003), the locomotion principles discussed in this work are applicable for microrobots ($\leq 1 \text{ cm}^3$) and minirobots ($\leq 1 \text{ dm}^3$).

Macroscopic robotic systems with volumes around cubic meters are often de-signed as rigid body systems with actuated joints (Zimmermann et al. 2009). Classical locomotion principles like rolling and walking are applied. In new fields of applications, especially in the vast fields of manufacturing engineering (handling and assembly of parts from micro fabrication), medicine (drug delivery, minimal invasive surgery, endoscopy), biology (handling of single cells, fluid injection into cells) and maintenance technology (inspection of hard-to-access areas, e.g. complex pipe systems), the application of classical robot designs is limited (Abbott et al. 2007; Sahu et al. 2010; Diller and Sitti 2013; Sitti et al. 2015; Bogue 2015). Systems are needed characterized by:

- small size and mass,
- minimal costs for production and application,
- great working space, and
- long operation time.

The adaption of established systems to the recent challenges by miniaturization is limited due to scaling properties of the physical effects that are used in classical actuators and joints. The production costs and energy consumption of classical systems rise substantially with decreasing physical dimensions. The coordinated control of several energy consuming actuators is needed to create complex multi-directional motion gaits.

Our aim is to show that locomotion principles based on vibrations can be used to create robots, which are suitable for recent requirements, with a minimal number of actuators. Driven by internal high-frequency vibrations, mobile robots can perform controllable locomotion with account of asymmetric system properties depending on frequency. From the methodological point of view it is focused on model-based design, which is not fully based on constructive know-how.

2 Locomotion Principles

The term *locomotion* is commonly used in the biological context and comprises processes of walking, crawling, climbing, digging, swimming, and flying (Zimmermann et al. 2009). That it is rather difficult to give a general definition from the mechanical point of view is discussed in Steigenberger (2011).

In general, actuating forces F_A are needed to be applied to realize locomotion. Resistive forces F_R impede the movement. It is focused on terrestrial locomotion which means that the actuation forces are created relative to a dry and solid ground. The motion of the system is not substantially deforming the environment.

2.1 Nature Inspiration

Nature has created organisms which can perform effective and energy efficient locomotion in any natural environment. Bionics researchers use biological examples for technical solutions (Lepora et al. 2013). Analyzing biological systems, the principles have been categorized, which can be applied to create terrestrial robots with a minimal number of actuators (Lysenko et al. 2007):

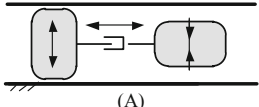
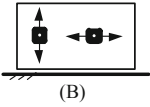
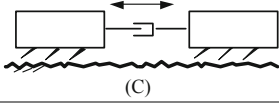
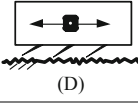
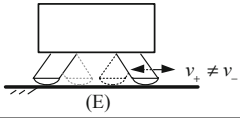
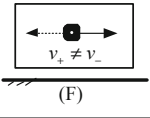
- reducing the number of active legs (kangaroo, basilisk),
- periodic change of the body shape (lizard, salamander),
- anisotropy of friction (earthworm, snake),
- multidimensional resonant vibrations of elastic extremities (mosquito).

2.2 Vibration Driven Locomotion

The microrobots considered in this paper are driven by internal actuators. As the deflection of the actuator in general is considerably smaller than the displacement of the robot, a periodic character of the internal excitation is needed. Systems with a periodic drive are called vibratory or undulatory locomotion systems (Ostrowski et al. 1995; Steigenberger 2011). Vibratory locomotion is characterized by “fast” actuation vibrations which overlay the “slow” translocation. Following Blekham (2000), it can be classified by means of a characteristic time interval. The maximal velocity of vibration driven robots can often be observed at an excitation close to the resonance of a system.

A great number of locomotion principles for microrobots are known from the literature. Using the Coulomb model of dry friction, a coherent classification for the motion on flat solid ground can be given (Driesen 2008). It is illustrated in Table 1.

Table 1 Classification of terrestrial locomotion principles based on dry (Coulomb) friction and vibratory actuation, following (Driesen 2008)

		Vibratory actuation	
		Relative motion	Inertia
Asymmetry in the system properties	Normal force $N_+ \neq N_-$	 (A)	 (B)
	Friction coefficient $\mu_+ \neq \mu_-$	 (C)	 (D)
	Actuation force $F_{A+} \neq F_{A-}$	 (E)	 (F)

The creation of a relative displacement between a system and environment can be divided into two principles:

- the contact points of the system to the environment can be moved relative to each other: (A), (C), and (E); or
- the inertias of internal masses, which have no contact to the environment and vibrate relative to the main body of the system, are used: (B), (D), and (F).

The principle (A) comprises systems which realize periodic contact forces in the contact points to the environment (Lobontiu et al. 2001). The changes of the forces are synchronized with the periodic relative displacement of the contact points to each other. It is illustrated in Table 1 by the well-known Inchworm principle. Walking and serpentine motion can be categorized in group (A) too.

Systems of category (B) create horizontal actuation forces by the vibrations of internal masses. The synchronized periodic change of contact forces, e.g. through the vertical vibration of an internal mass, leads to the overall displacement of the system (Bolotnik and Figurina 2008; Zhan et al. 2015).

The principles (C) and (D) are based on the frictional design of the contact areas of the system. The motion in one direction is promoted. It can be modeled with anisotropic friction coefficients. Worm-like locomotion systems (C) are inspired by the peristaltic locomotion of earthworms (Steigenberger and Behn 2012; Gidoni et al. 2014; Bolotnik et al. 2016). They are consisting of two or more segments which can be displaced relative to each other in the direction of motion. If the horizontal force is created by the vibration of an internal mass (D) the system can be constructed without vibrating elements in contact to the environment.

The principles (E) and (F) are based on asymmetric actuation forces. It means that over a period of vibration the values of the acceleration in forward and backward direction differ. Examples are the stick-slip-drive and the inertia drive. Both mechanisms are realized in the field of microrobotics (Eigoli and Vossoughi 2010).

The energetic costs of different locomotion principles are an important point for their application. Especially compared to the rolling motion, the presented principles cannot compete in terms of efficiency. The vibration-driven locomotion is based on differences in the friction properties over a period of the actuation. Periodic sliding motions in forward and backward direction are the usual case. Rolling systems do not have these disadvantages. The potential of the discussed principles lies in the application in environments, which are inappropriate for rolling locomotion, e.g. small maneuvering space or micro scale environments.

3 Locomotion Based on Low and High Frequency Vibration Drives

Robots of micro and mini dimensions for two-dimensional locomotion on flat solid ground are state of the art. Piezoelectric (bending) elements are suitable actuation solutions within the proposed dimensions (1 cm^3 – 1 dm^3).

Mobile robotics and drive technology are related subjects. Some of the principles discussed in Table 1 are used in piezoelectric motors (Uchino 1998; Janocha 2013; Peng et al. 2015). Examples are inchworm drive, LEGSTM motor, stick-slip principle, and ultrasonic motors. The characteristic conflict of objectives in drive technology between positioning accuracy and actuation speed is present in mobile robotics too.

Inspired by drive technology, mobile micro robots can be divided into quasi-static and resonant systems.

3.1 Quasi-static Mobile Robots

The frequency of the internal actuation vibration of quasi-static robots is considerably smaller than the first natural frequency f_0 of the actuator or a mechanical transmission element. The advantage of such design is the high positioning accuracy: “atomic resolution” (Besocke 1987). Compared to resonant systems, such robots are slow due to the small step size and an excitation with a frequency in the range of $f = 0.01f_0 \dots 0.1f_0$.

Typical quasi-static mobile robots deploy the following principles: walking (Baisch et al. 2011; Hoffman and Wood 2011; Li et al. 2011), inchworm (Yan et al. 2002; Lee et al. 2015), earthworm (Kim et al. 2005), stick-slip and inertia drive (Rembold and Fatikow 1997; Farahani et al. 2012). Within the European project MiCRoN (Estaña and Woern 2007), miniaturized autonomous robots have been developed. Using the stick-slip principle, the MiCRoN-robots can move with a step size down to 10 nm and a speed of 0.4 mm/s.

3.2 Resonant Mobile Robots

Resonant robots are excited by vibration frequencies close to the natural frequencies of elastic mechanical systems, i.e. actuators or transmission elements. Typical realizations are based on piezoelectric bending elements, which excite elastic beams or plates to perform forced vibrations. The internal vibrations are transformed by frictional periodic contacts into motion. The main aim of using the resonance in mobile robots is to achieve an advanced mobility. The systems reported in the literature follow two different vantage points:

1. use of a single natural mode to maximize the robot velocity while minimizing the energy consumption,
2. use of different natural modes to create multidirectional locomotion abilities while minimizing the number of actuators.

Maximizing velocity

The deflection of an actuator or a mechanical transmission element is maximized because of the excitation with a frequency close to a natural frequency. Usually the second natural mode of elastic beams, or the third up to sixth natural mode of a thin elastic plate are used. Anyway, the step size of robots in the considered dimension depends on the concrete design, but it lies typically in the range from nano meters up to micro meters. Using a high excitation frequency from 1 to 100 kHz, fast systems can be designed. Disadvantages can be found in the positioning accuracy and control properties.

Examples of robots based on resonant vibrations are given in Asano et al. (1995), Daugela (1995), DeAmbroggi et al. (1997), Ferreira and Minotti (1997), Woern et al. (2006), Ferreira and Fontaine (2003), Son et al. (2006), Nguyen and Martel (2007), Snis (2008), Avirovik et al. (2014), Hariri et al. (2015), Rios et al. (2015). Within the European I-SWARM project (Woern et al. 2006), autonomous robots for swarm applications have been developed using piezoelectric elastomers (Edqvist 2009). The contributions show that it is rather difficult to achieve a pre-defined frequency dependent locomotion characteristic. In Snis (2008) it is reported that within the I-SWARM project the frequency dependent behavior of every agent needed to be obtained experimentally, as the used second natural frequency could differ around 2 kHz from one agent to another.

Realizing multidirectional locomotion

Early contributions considering the use of different natural modes of a single elastic system to perform multidirectional locomotion are given in Asano et al. (1995), Ferreira and Minotti (1997). The actuator presented in Ferreira and Minotti (1997) consists of a passive metal plate with a fixed bar which creates the frictional contact to the solid ground. A matrix of 4×5 piezoelectric ceramic patches is fixed on the system. A synchronized excitation of the piezoelectric elements excites forced vibrations. Using different normal modes, the two-dimensional locomotion can be performed. Degenerated modes allow the rotation of the system. In Ferreira and

Fontaine (2003), a miniaturized system on that basis is presented which consists of 48 such elastic coupled elements. A similar system for one-dimensional locomotion is studied by Son et al. (2006). It uses six piezoelectric patches. In Hariri et al. (2015) it is shown that the idea of Son et al. (2006) can be realized using only one actuator.

4 Multidirectional Resonant Robots

The robots presented in Chap. “A Biologically Inspired Sensor Mechanism for Amplification of Tactile Signals Based on Parametric Resonance” use several actuators to perform two-dimensional locomotion. The deployed principle is based on periodic changes in the frictional contacts between a robot and a solid ground. Similar systems using only one actuator for two-dimensional locomotion are presented in Abaza (2007), Becker et al. (2012). In this paper, the vibration driven locomotion principle is discussed by means of an exemplary prototype.

4.1 Prototype Design

The prototype shown in Fig. 1 consists of a circular piezoelectric plate with three fixed legs made from copper. The legs have contact points to the flat solid ground, i.e. they are acting as vibration transducer. Characteristic values of parameters of the prototype and its actuator are given in Table 2. The robot is driven by a high frequency AC voltage, which is applied to the piezoelectric bending element.

Fig. 1 Robot prototype consisting of a circular piezoelectric bending element and three legs

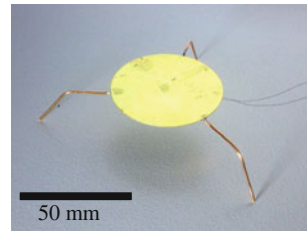


Table 2 Characteristic data of the prototype and actuator

Robot prototype		Actuator	
Diameter $\varnothing \times$ height	80 mm \times 15 mm	Piezo patch	\varnothing 30 mm \times 0.2 mm
Mass	6 g	Brass plate	\varnothing 50 mm \times 0.2 mm
Max. velocity	25 mm/s (on glass)	AC voltage	24 V (0.5–20 kHz)

4.2 Motion Principle and Control

The piezoelectric element vibrates with the frequency of the applied AC voltage and excites the legs to perform bending vibrations. Due to arising complex trajectories of their endpoints the contact and friction properties periodically change. The actuator and the legs with their slightly different geometry form a non-symmetrical vibration system. The endpoint trajectories of each leg differ from each other. Therefore, the resonance characteristic of the elastic overall system can be used to influence on the vibration behavior of every endpoint individually. The locomotion of the system can be controlled by the applied excitation frequency.

To study this phenomenon experimentally, the robots' motion is filmed from above for different frequencies. Two motion markers fixed on the robot are tracked automatically. Results are presented in Fig. 2. The diagram shows dependencies of the translational and rotational velocity on the robots' excitation frequency. The translational velocity is calculated from the trajectory length of the center point of the robot divided by the motion time. The rotational speed gives the change of the robots' orientation in the plane over time. To illustrate the locomotion, three sub-figures are added in Fig. 2. For three example frequencies, they illustrate the motion of the prototype by means of an overlay of video frames. The added arrow indicates the locomotion direction.

The motion trajectories of the robots are reproducible. However, our studies (Becker et al. 2012; Becker 2015) and the review of the literature show that it is rather difficult to create robots with predefined locomotion characteristics. Disparities in the used actuators and manual fabrication methods, e.g., soldering and bending, lead to robots with slide structural differences and the varying locomotion behavior of the individual prototypes for the same frequencies. Furthermore,

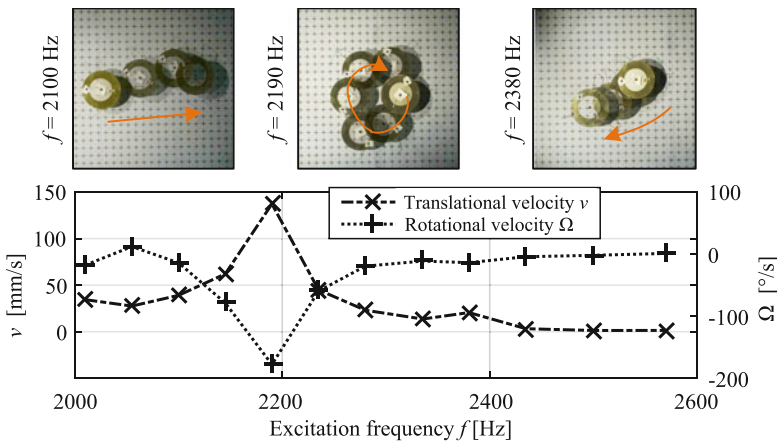


Fig. 2 Locomotion of the prototype excited with a frequencies close to the second natural frequency of a leg $f_2 = 2335$ Hz

the locomotion behavior depends on the substrate of the ground on which the robot is moving on (Becker et al. 2012) and the current mechanical load of the system (Becker 2015). To achieve an automatic control, a teaching process for every single robot is needed.

4.3 Modeling and Simulation

The vibration behavior of the legs has a major influence on the locomotion. The second resonance frequency of an idealized leg, which is considered as a straight Euler-Bernoulli beam with fixed-free support conditions, can be obtained with

$$f_2 = \frac{3.507}{L^2} \cdot \sqrt{\frac{EI_z}{\rho A}} \tag{1}$$

For the parameters of a leg of the presented robot, it follows $f_2 = 2335$ Hz. If the actuator is excited with a frequency close to it, the robot shows a local maximum in translational and rotational speed, as it is presented in Fig. 2. These results confirm the statements in DeAmbroggi et al. (1997), Snis (2008).

To study the described behavior numerically, the finite element method (FEM) is used. The robot is modeled by volume and line elements with and without piezoelectric abilities respectively. Rheonomic conditions are used to fix the center nodes of the actuator. An AC voltage is applied on the boundary of the piezoelectric volume elements. The results presented in Fig. 3 are obtained by the harmonic analysis of the FEM model. The second natural mode of the model is given from two perspectives, and two characteristic points are marked. Additionally, the diagram shows the vibration amplitudes of these points. The local maximum of the amplitude can be found close to the resonance frequency of a single leg. The results

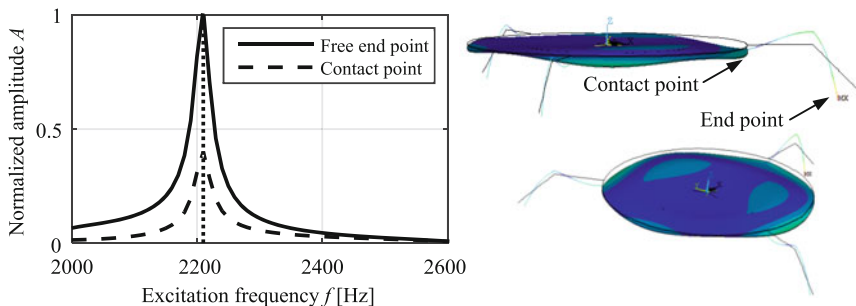


Fig. 3 FEM results: normalized amplitude of characteristic points obtained with the numerical harmonic analysis of the centric fixed model around the second natural frequency of the leg and vibration mode of the model

obtained numerically and experimentally agree with each other. Resonance behavior can be used to maximize the vibration amplitude of the legs' endpoints and, therefore the speed of robots.

5 Conclusions

Vibration-driven locomotion principles are extensively applied in microrobotics. They can be classified by the deployed mechanisms to create the needed asymmetry in the system characteristics or, inspired by drive technology, by the magnitude of the excitation frequency. Quasi-static robots are driven with a frequency considerably smaller than the first natural frequency. A high positioning accuracy, good control properties and a small speed can be achieved. Resonant robots use the frequency-dependent behavior of elastic mechanical elements and actuators to realize fast systems or a multidirectional control. The number of actuators can be minimized.

Robots for multidirectional locomotion can be designed with a single actuator deploying the principle of vibratory locomotion. The dynamics of the legs of a robot has a major influence on the locomotion. The motion trajectories are reproducible, high velocities are achieved. The direction of motion of resonant robots is controlled by the frequency-dependent vibration modes of elastic systems. This control strategy causes special difficulties as the high frequency vibration behavior strongly depends on the boundary conditions and properties of the elastic system. Using prototype manufacturing technologies, it is rather difficult to create robots with a predefined behavior. The frequency-locomotion characteristics need to be obtained individually for every single robot and all combinations of environmental conditions and mechanical loadings. If these characteristics are obtained, it is possible to create locomotion in a precisely desired fashion.

Future extensions of this work will be oriented to increase the robustness of the systems to parameter changes of the environment and robot manufacturing. It should be possible to create robots with a predefined frequency-dependent locomotion behavior. Advanced manufacturing technologies could be applied.

Acknowledgments The research work reported here was partly supported by Deutsche Forschungsgemeinschaft Grant ZI 540/19-1.

References

- Abaza K (2007) Ein Beitrag zur Anwendung der Theorie undulatorischer Lokomotion auf mobile Roboter. Dissertation, TU Ilmenau
- Abbott JJ, Nagy Z, Beyeler F, Nelson BJ (2007) Robotics in the small: P. 1. microrobotics. IEEE Robot Autom Mag 14(2):92–103

- Asano M, Matsuoka T, Okamoto H et al (1995) Study for micro mobile machine with piezoelectric driving force actuator. In: Proceedings of the IEEE international conference on robotics and automation (ICRA), vol 3, pp 2955–2960
- Avirovik D, Butenhoff B, Priya S (2014) Millipede-inspired locomotion through novel U-shaped piezoelectric motors. *IOP Smart Mater Struct* 23:1–5
- Baisch AT, Heimlich Ch, Karpelson M, Wood RJ (2011) HAMR³: an autonomous 1.7 g ambulatory robot. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems (IROS), pp 5073–5076
- Becker F (2015) Zur Mechanik vibrationsgetriebener Roboter für terrestrische und aquatische Lokomotion. Dissertation, TU Ilmenau
- Becker F, Minchenya V, Zimmermann K et al (2012) Single piezo actuator driven micro robot for 2-dimensional locomotion. In: *Micromechanics and microactuators*, vol 2. Springer, Berlin, pp 1–10
- Besocke K (1987) An easily operable scanning tunneling microscope. *Surf Sci* 181:145–153
- Blekhman II (2000) *Vibrational mechanics: nonlinear dynamic effects, general approach, application*. World Scientific, Singapore
- Bogue R (2015) Miniature and microrobots: a review of recent developments. *Ind Robot* 42(2): 98–102
- Bolotnik N, Figurina T (2008). Vibration-driven systems with movable internal masses: control and optimization. Proceedings of the 53rd international scientific colloquium, Ilmenau, 8–12 Sept 2008, pp 31–32
- Bolotnik N, Pivovarov M, Zeidis I et al (2016) The motion of a two-body limbless locomotor along a straight line in a resistive medium. *Z Angew Math Mech* 4:429–452
- Caprari G (2003) *Autonomous micro-robots: applications and limitations*. Dissertation, École polytechnique fédérale de Lausanne
- Daugela A, Fujii H, Jeronymo CE et al (1995) Piezo ceramic based locomotive drive. In: Proceedings of the 6th IEEE international symposium of micro machine and human science, pp 187–192
- DeAmbroggi F, Fortuna L, Muscato G (1997) PLIF: piezo light intelligent flea-new micro-robots controlled by self-learning techniques. In: Proceedings of the IEEE international conference on robotics and automation (ICRA), vol 2, pp 1767–1772
- Diller E, Sitti M (2013) Micro-scale mobile robotics. *Found Trends Robot* 2(3):143–259
- Driesen W (2008) Concept, modeling and experimental characterization of the modulated friction inertial drive (MFID) locomotion principle: application to mobile microrobots. Dissertation, École polytechnique fédérale de Lausanne
- Edqvist E, Snis N, Mohr R et al (2009) Evaluation of building technology for mass producible millimetre-sized robots using flexible printed circuit boards. *J Micromech Microeng* 19(7)
- Eigoli AK, Vossoughi GR (2010) Dynamic modeling of stick-slip motion in a legged piezoelectric driven microrobot. *Int J Adv Robotic Syst* 7(3):201–208
- Estaña R, Woern H (2007) The MiCRoN robot project. *Informatik akutell, Autonome mobile systeme*. Springer, Berlin, pp 334–340
- Farahani AA, Suratgar AA, Talebi HA (2012) Optimal controller design of legless piezo capsbot movement. *Int J Adv Robot Syst* 10(126):1–7
- Ferreira A, Fontaine J (2003) Dynamic modeling and control of a conveyance microrobotic system using active friction drive. *IEEE-ASME T Mech* 8(2):188–202
- Ferreira A, Minotti P (1997) Control of a multidegree of freedom standing wave ultrasonic motor driven precise positioning system. *Rev Sci Instrum* 68(4):1779–1786
- Gidoni P, Noselli G, DeSimone A (2014) Crawling on directional surfaces. *Int J Non-Linear Mech* 61:65–73
- Hariri HH, Soh GS, Foong SH et al (2015) Miniature piezoelectric mobile robot driven by standing wave. Proceedings of the 14th world congress in mechanism and machine science, pp 1–6
- Hoffman KL, Wood RJ (2011) Passive undulatory gaits enhance walking in a myriapod millirobot. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems (IROS), pp 1479–1486

- Janocha H (2013) *Unkonventionelle Aktoren: Eine Einführung*. Oldenbourg Verlag, München
- Kim B, Park S, Jee CY et al (2005) An earthworm-like locomotive mechanism for capsule endoscopes. In: Proceedings of the 2005 IEEE/RSJ international conference on intelligent robots and systems, 2–6 Aug 2005, pp 2997–3002
- Lee K, Kim Y, Park JK et al (2015) Clawed miniature inchworm robot driven by electromagnetic oscillatory actuator. *J Bionic Eng* 12(4):519–526
- Lepora NF, Verschure P, Prescott TJ (2013) The state of the art in biomimetics. *Bioinspir Biom* 8(1):013001
- Li W, Li J, Hu, H et al (2011) Analysis and experiment of stick-slip motion principle in a legged microrobot. In: Proceeding of the 6th forum on strategic technology, vol 1, pp 328–332
- Lobontiu N, Goldfarb M, Garcia EA (2001) A piezoelectric-driven inchworm locomotion device. *Mech Mach Theory* 36(4):425–443
- Lysenko V, Minchenya W, Zimmermann K (2007) Minimization of the number of actuators in legged robots using biological objects. In: Proceedings of the 52nd international scientific colloquium, Ilmenau, 10–13 Sept 2007, pp 483–488
- Naguyen AT, Martel S (2007) Locomotion of a miniature robot based on synchronized vibrating actuation mechanisms. In: Proceedings of the IEEE/ASME international conference on advanced intelligent mechatronics (AIM), pp 1–6
- Ostrowski J, Burdick J, Lewis AD et al (1995) The mechanics of undulatory locomotion: the mixed kinematic and dynamic case. In: Proceedings of the IEEE international conference on robotics and automation (ICRA), vol 2, pp 1945–1951
- Rembold U, Fatikow S (1997) Autonomous microrobots. *J Intell Robot Syst* 19(4):375–391
- Rios SA, Fleming AJ, Yong YK (2015) Design of a two degree of freedom resonant miniature robotic leg. In: Proceedings of the IEEE international conference on advanced intelligent mechatronics (AIM), pp 318–323
- Sahu B, Taylor CR, Leang KK (2010) Emerging challenges of microactuators for nanoscale positioning, assembly, and manipulation. *J Manuf Sci Eng* 132(3):030917-1–16
- Sitti M, Ceylan H, Hu W et al (2015) Biomedical applications of untethered mobile milli/microrobots. *Proc IEEE* 103(2):205–224
- Snis N (2008) Actuators for autonomous microrobots. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 431, Uppsala University
- Son KJ, Kartik V, Wickert JA et al (2006) An ultrasonic standing-wave-actuated nano-positioning walking robot: piezoelectric-metal composite beam modeling. *J Vib Control* 12(12):1293–1309
- Steigenberger J (2011) Some theory towards a stringent definition of ‘locomotion’. *Multibody Syst Dyn* 26(1):81–90
- Steigenberger J, Behn C (2012) *Worm-like locomotion systems: an intermediate theoretical approach*. Oldenbourg Verlag, München
- Uchino K (1998) Piezoelectric ultrasonic motors: overview. *Smart Mater Struct* 7:273–285
- Woern H, Szymanski M, Seyfried J (2006) The I-SWARM project. In: Proceedings of the 15th IEEE international symposium on robot and human interactive communication, pp 492–496
- Yan G, Lu, Q, Ding G et al (2002) The prototype of a piezoelectric medical microrobot. In: 13th IEEE international symposium of micromechtronics and human science, pp 73–77
- Yuxin P, Yulong P, Gu X et al (2015) A review of long range piezoelectric motors using frequency leveraged method. *Sensor Actuat A-Phys* 235:240–255
- Zhan X, Xu J, Fang H (2015) Planar locomotion of a vibration-driven system with two internal masses. *Appl Math Model*. <http://dx.doi.org/10.1016/j.apm.2015.06.016>
- Zimmermann K, Zeidis I, Behn C (2009) *Mechanics of terrestrial locomotion*. Springer, Berlin