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Insect-inspired drive strategy substantially improves the performance of a piezo motor

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ABSTRACT

Bioinspiration has been a driving force behind the design of various solid-state actuators. While in nature the structure of an animal and the control mechanisms have co-evolved and perform best when used together, biologically-inspired actuators often employ oversimplified technical drive solutions. The piezo motor discussed in this work is an example of such a device. It consists of four leg-like elements which need to interact with a ceramic bar in a stable way. This work presents a novel bioinspired drive mechanism for this motor. Specifically, an architectural mapping between a model of walking in insects and the piezo motor is proposed. In the insect-inspired strategy, all piezoelectric legs are allowed to be driven independently and not in pairs as opposed to the classical drive strategy. Based on the physical model of motor dynamics, it is shown that the insect-inspired approach substantially improves the performance of the motor in terms of its force generating capabilities as well as maximal drive velocity. Furthermore, the novel approach is described by a moderate number of intuitive parameters and produces a variety of velocity-dependent gaits as known from the research on animals.

1. Introduction

The possibility to actively and purposefully change one or more properties of a smart material reduces the gap between the technical and biological building blocks of complex systems. Examples range from smart biocompatible materials [1] to artificial muscles [2] and miniature robots [3,4]. Piezoelectric materials have virtually dominated the field of small-sized actuation not only due to their size-insensitive efficiency [5] and a cost-efficient manufacturing technology [6], but also due to the utilization of novel biologically-inspired and material-based actuation mechanisms. Uchino [7] enumerates several resonant motors whose working principle can be compared to the movement mechanism of Euglena, Paramecium or Ameba. Other examples include the quasi-static inchworm [8] or the walking motor [9,10]. These devices are bioinspired in the sense that they employ hair- or leg-like solid-state actuation units. However, their control strategy rarely relies on biological findings. In this work, a biologically inspired control strategy is introduced which significantly improves the performance of a walking motor.

1.1. Classical drive strategy

The piezoelectric walking motor consists of four leg-like multilayer PZT bimorph actuators (legs) – see Fig. 1(a). Each leg i is controlled by means of two electrical phases $U^A_{(i)}$ and $U^B_{(i)}$ with $i \in \{1, \ldots, 4\}$. The legs are hard-wired to move in pairs of two legs which interchangeably establish a frictional contact to a movable slider (drive rod) [11]. Classically, the drive strategy consists of an ordered sequence of contact–release cycles which are realized with help of centrally generated electrical waveforms with a fixed phase relation between them. Neglecting short transition periods, only one pair of legs contacts the slider at any time [11]. The particular shape of the waveforms has a significant influence on the performance of the walking motor [11,12]. Simu and Johansson [13] proposed two rudimentary drive strategies similar to the stick-slip and impact drive mechanisms [14] which result in a relatively high motor speed on the cost of high velocity fluctuations and a poor load capacity due to the inherent slip phases. In the same work, they proposed a trapezoidal and sinusoidal waveforms which reduce the slip. Building on their results, Merry et al. [15]

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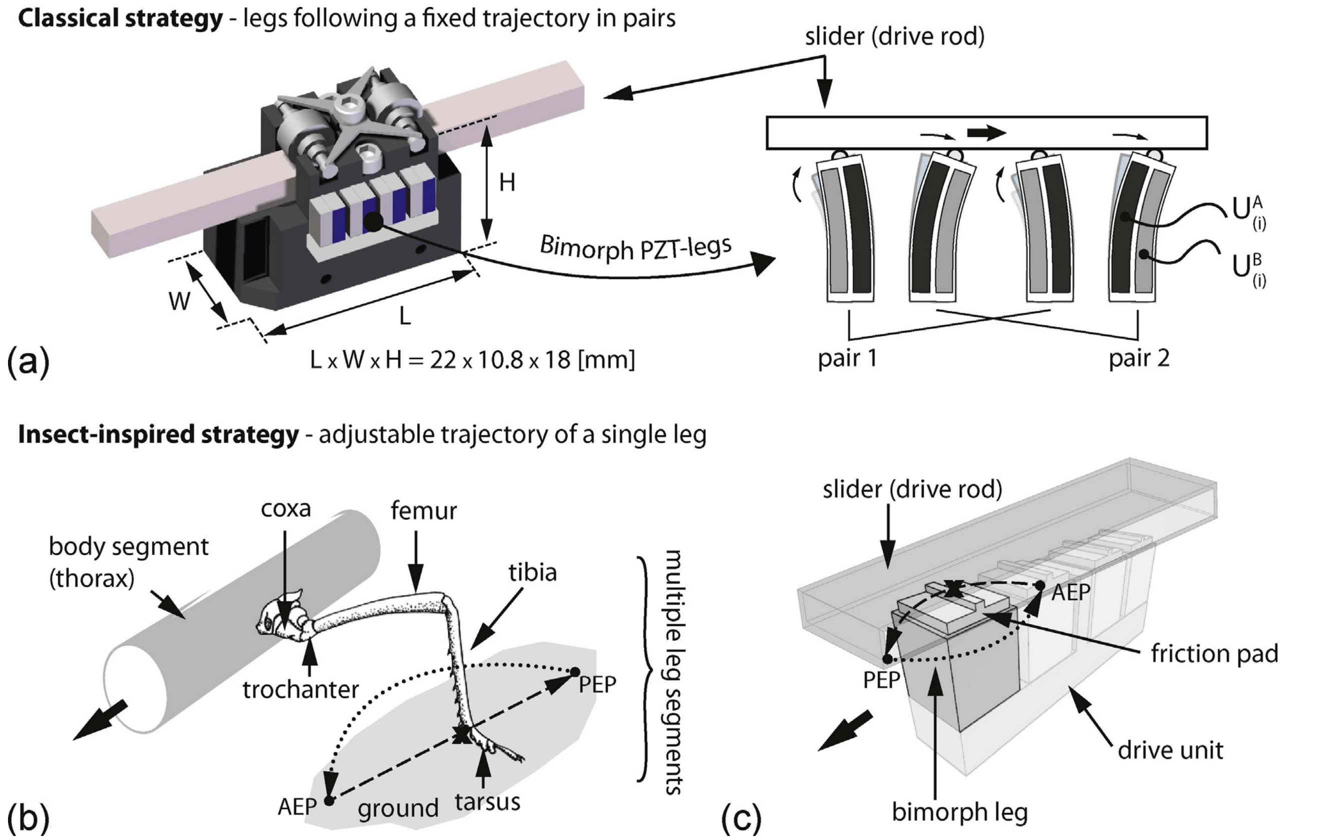

Fig. 1. Piezoelectric motor (a) consisting of four PZT leg-like elements and a movable slider. The legs are hard-wired for an operation in pairs. In (b) and (c) a schematic depiction of an insect leg and a piezoelectric leg performing one walking cycle is shown. (b) The insect leg consists of several segments connected with joints resulting in three functional DOFs. (c) The piezoelectric leg is a multilayer bimorph bender which can perform an in-plane movement (stance/power phase as dashed line, swing phase as dotted line). The trajectories in (c) are highly exaggerated. The resulting directions of motion are indicated with a thick arrow for both insect's body and the drive rod of the motor.

parametrized the sinusoidal waveform and derived an asymmetrical waveform which improves motor velocity constancy on the cost of a lower drive velocity. In a later work, Merry et al. followed this strategy and proposed an optimization strategy based on 4th order Fourier series description of the waveforms [12]. Each of the 4 waveforms was described by 8 different parameters, resulting in altogether 32 parameters. As a result, motor velocity constancy could be improved on the cost of further motor velocity decrease. However, their strategy is based on an extensive optimization process with a dedicated solver. The high-dimensional solution is highly susceptible to manufacturing differences in individual motors [12], thus questioning the actual performance gain in practical applications. Furthermore, the influence of external loading is not considered in the above works which focus on the positioning capabilities of the motor. The walking motor, however, comes with exceptional force-generation capabilities for a motor of its size [16] which could be further improved if more than two legs contacted the slider.

1.2. Novel drive strategy inspired by insect walking

The difficulty of improving the performance of the motor by varying the shape of the driving signals with help of a computationally-intensive, high-dimensional optimization task indicates the limits of the classical pairwise drive strategy with fixed phase relations. Considering the fact that the drive principle of the motor is based on “walking”, it is useful to look for a biologically inspired solution since even simple animals like insects solve this problem efficiently. In this context, insects are especially interesting because of their multitude of legs which they need to coordinate during walking. Fig. 1 illustrates an insect (b) and a motor leg (c) schematically during one walking cycle. An insect leg is functionally a 3 DOF serial manipulator consisting of multiple segments connecting rotary joints. A piezoelectric leg is a 2 DOFs piezoelectric bender. For an in-plane motion, the former is redundant while the latter is not. The walking cycle of an insect leg consists functionally of two stages – the power stroke (also called the stance or support phase) and the return stroke (also swing or recovery phase). During the power stroke, the leg contacts the ground where it can support and propel the body. During the return stroke, the leg is lifted off the ground and swung freely to the starting position for the next power stroke [17]. This starting position is called the *anterior extreme position* (AEP) (also touch-down position). While performing the power stroke, the leg moves toward the *posterior extreme position* (PEP) (also lift-off position) from which the next return stroke is started. These are indicated in Fig. 1(b) and (c) with dashed and dotted lines, respectively. Note that due to the difference in the static vs. movable “ground” concept, the directions of power and return strokes are swapped for the insect and piezoelectric legs given the indicated direction of motion. The current leg position in the walking cycle is marked with an ×-marker by which the position of a leg tip (tarsus base or friction pad center) is meant. Thus both legs in the schematic depiction are in the middle of their power strokes. Also note the difference in the shape of the power stroke trajectory. While it resembles a straight line compared to the arched return stroke in case of the insect, it has an arched shape in case of both the power and return strokes in the motor. These shapes are due to the differences in the relative compliance of the legs and the “grounds” which they touch.