Locomotion principles for piezoelectric miniature robots

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Locomotion principles for piezoelectric miniature robots

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Abstract:
Piezoelectric miniature robots are mobiles robots with a size of a few cm³ actuated by piezoelectric materials. In this paper, we will study the locomotion principles for piezoelectric miniature robots. They are mostly inspired from the animal locomotion and are classified by their displacement through a fluid medium or on a solid substrate. We will discuss wheeled locomotion, walking locomotion, inchworm locomotion, inertial drive, resonant drive, and friction drive as locomotion’s on a solid substrate. In liquid, locomotion for mobile miniature robots is totally inspired from animal locomotion and is divided into locomotion inside liquid and locomotion at the liquid surface. A brief description of animal locomotion in liquid is given. In air, locomotion for mobile miniature robots is divided into flapping wings, rotary wings, fixed wings and gliding wings. Flapping wings is the only method described in this paper. After definition of each locomotion principle, some piezoelectric miniature robots are taken as examples and an important review is given.

Keywords: piezoelectric miniature robots, piezoelectric actuators, locomotion principles

1. Introduction

In this paper, the term mobile miniature robots will represent robots with a size of less than 1 dm³ and a motion range of at least several times the robots body length. Then piezoelectric miniature robots are mobile miniature robots actuated by piezoelectric materials. Mobile miniature robots capable to do many applications that can not be done with robots, such as cell storing, research objects in narrow areas or on swarm behavior, espionage, surveillance for security, medical applications &c. Manufacturing of multilayer piezoelectric actuators and bending piezoelectric actuators have the potential to eliminate the drawbacks of piezoelectric materials and make them among the most commonly used in mobile miniature robots. Piezoelectric actuators are responsible for motion and are characterized by two energy transformations. The electrical to mechanical conversion and the mechanical to mechanical conversion. The first conversion reflects the reverse piezoelectric effect, which generates small motion of mobile miniature robots. The second conversion containing specific locomotion principles amplifies the motion of mobile miniature robots. Locomotion principles for mobile miniature robots are mostly inspired from animal locomotion and are classified by their displacement through a fluid medium or on a solid substrate. In this paper, we will study these locomotion principles and some piezoelectric miniature robots are taken as examples.

2. Locomotion on a solid substrate

The forces related to motion on land are the force of gravity, the normal reaction, the friction force, which depends on friction coefficient and contact force and the active force that generates the motion. Locomotion on a solid substrate for mobile miniature robots includes wheeled locomotion, walking, inchworm, inertial drive, resonant drive and friction drive. We will describe in this section, these locomotion principles.

2.1. Wheeled locomotion

The principle is based on small engines powering the wheels. These engines can be DC motors, step motors, or piezoelectric motors. As examples for wheeled locomotion in miniature robots driven by piezoelectric materials, we can count references [1 & 2].

2.2. Walking locomotion

The principle of this locomotion is based on legs which are the drive units, to achieve a movement similar to the biological organism. In walking mechanisms for mobile miniature robots, the legs are fixed on the robot and they are divided into two sets, where each set alone can maintain the equilibrium of robot. The legs maybe thermal, polymer, electrostatic or piezoelectric drives units. In this paper, we are interested in the piezoelectric actuators and they are generally multilayer benders or monolithic multilayer. Walking is essentially a quasistatic locomotion, at high frequency, the control of drive unit can cause motion instabilities, for this reason it is advisable to work in quasi static mode. We can count as examples for walking locomotion in piezoelectric miniature robots references [3-7].

2.3. Inchworm locomotion

An inchworm device consists of 3 actuators, two clammers and one extensor. The extensor one is always between the two clammers. The clamper is
used to clamp the device into the substrate while the extensor generates the stroke required for the displacement. As examples for inchworm locomotion in piezoelectric miniature robots, we can count references [8-14].

2.4. Inertial drive

The inertial drive principle is generated in the case of asymmetric actuation, i.e. in the case of rapid extension (or contraction) and slow contraction (or extension) of the actuator; so the command signal of the actuator must be a sawtooth signal; for this reason, most of miniature robots based on inertial drive principles are actuated by piezoelectric actuators, because of their high bandwidth. Two types of inertial drive principles can be distinguished: the stick-slip principle and the impact drive principle. This distinction is due to the difference in the design of the device (Fig. 1). A stick-slip design consists of an inertial mass which is the main body; legs which are the piezoelectric drive units, and are fixed in the inertial mass; and a contact surface which is fixed in the legs. An impact drive design consists of an inertial mass connected to the main body via a piezoelectric element, due to its design, the impact drive is typically driven by a sawtooth signal with a quadratic ramp phase to enable store a maximum amount of kinetic energy in the motion of the inertial mass, resulting in the maximum step displacement of the body of the robot [15]. Schematics diagrams describe steps of motion for each device can be found in [16]. Many piezoelectric miniature robots are based on the inertial drive principles, as examples we can take references [17-20].

Fig.1: Stick-slip (left) and impact drive (right) design

2.5. Resonant drive

Resonant drive mechanisms are frequently used in the field of ultrasonic motors (USM). For mobile miniature robot the resonant motion is related to the standing wave type (SWUM) and it is defined in [15] by inertial slip generation with contact force variation. According to this definition, the motion is generated by variation of the contact force, where the contact force variation is the inertial effect of a vertical vibration, which results from the back-and-forth motion of the robot body. We can summarise that the inertial force is generated by the horizontal vibration of the robot body. Therefore to increase the inertial force, the horizontal vibration must be increased, this requires increasing the frequency of feet vibration. Motion occurs when this inertial force becomes larger than the maximum friction force between feet and substrate. So we must increase the frequency until a threshold where motion occurs. As examples for piezoelectric mobile miniature robot using this mode, we can count references [21-25].

2.6. Friction drive

In this case, the generation of motion is due to the change of friction coefficient during horizontal vibration of robot body. The change of friction coefficient results from a no-perpendicular contact angle between robot feet and substrate. It differs from the resonant drive by the fact that, in the resonant drive the horizontal vibration generates the inertial vibration, that in turn generates the motion of the robot; in the friction drive, no inertial force vibration occurs during horizontal vibration but a change in the friction coefficient, which causes a motion in the direction of low friction without intervention of the inertial force. As examples for piezoelectric miniature robots using this mode, we can take references [26-28].

3. Locomotion in liquid

The movement in liquid is totally inspired from animal locomotion and is divided into locomotion inside liquid and locomotion at the liquid surface. The design of miniature robots in aquatic medium depends on the liquid properties; the forces were acting on and some factors influencing the locomotion. The forces acting on miniature robots inside liquid are thrust, drag, weight buoyancy and hydrodynamic lift (Figure 2). The thrust here is defined as the force generated by moving portions of the miniature robot body on the fluid surrounding it, to move miniature robot forward. The inertial force depends on the body mass while the buoyancy force is generated by fins and it depends on the mass of fluid displaced. The hydrodynamic lift is generated by fins to supplement buoyancy and balance the vertical forces when horizontal motion is demanded. The drag is the resistive force exerted by the fluid on its body and it consists of viscous drag and pressure drag. Viscous drag is skin friction between the miniature robot and boundary layer of water. The pressure drag exerted by distortions of flow around miniature robot body and energy lost in
the vortices formed by the fins as they generate lift or thrust. At the liquid surface, the forces acting on miniature robots are the same but in this case the miniature robots use the surface tension of liquid which represents the work required to deform a liquid over a unit area [29] to generate lift, buoyancy and thrust, or they use the mass density of liquid to generate these forces. An important factor influencing the locomotion for miniature robots in liquid is the Reynolds number (Re) that describes the viscous versus inertial forces. At low Re viscous forces reign, but at high Re inertial forces dominate. This has important consequences for the propulsive mechanisms and design for locomotion at low and high Re [29]. The Froude number (Fr) is also an important factor that describes the propulsive efficiency of the miniature robots. It is the ratio of the useful propulsive power over the total power expended by the mobile miniature robots. As already mentioned the design of miniature robots in aquatic medium depends on surface tension of liquid, density of liquid, Reynolds number and the forces were acting on, locomotion principles itself are not influenced by the type of liquid. So, the study of locomotion principles in any type of liquid is the same, we then consider the case of water in the following. As the movement in liquid for mobile miniature robots is totally inspired from animal locomotion, a study of animal locomotion in water is given in this section, with some applications in the field of piezoelectric miniature robots.

3.1. Locomotion inside water

Locomotion inside water includes swimming or non-swimming locomotion. The latter includes specialized actions such as flying and gliding, as well as jet propulsion. In this section, we will describe only the swimming locomotion because it is the most used in the field of miniature robot and it is divided into fish swimming mechanisms (at high and moderate Re) and micro-organisms swimming mechanisms (at low Re).

3.1.1. Fish swimming mechanisms

To aid in the description of fish swimming mechanisms; Fig. 3 identifies the elements of fish. The fish swim either by body and/or caudal fin (BCF) movements or using median and/or paired fin (MPF) propulsion. The BCF propulsion has been classified into five swimming modes: Anguilliform, subcarangiform, carangiform, thunniform and ostraciform. The latter is the only oscillatory BCF mode; it is characterized by the pendulum oscillation of the caudal fin, while the body remains essentially rigid. While the others are undulatory BCF modes. In anguilliform mode, ondulations of large amplitude are obtained by whole body. Similarly for subcarangiform mode, but the amplitude of undulations is limited in front and increased in the latter half of the body. For carangiform mode, the amplitude of the undulations is limited to the last third of the body. In thunniform mode, the thrust is generated by the caudal fin only. The MBF propulsion has been classified into seven swimming modes: Rajiform, diodontiform, amiiform, gymnnotiform, balistiform, labriform and tetraodontiform. The two latter modes are classified into undulatory fin motions, while the five remaining are classified into oscillatory fin motions. In rajiform mode, the most of the body length undulate vertically along the pectorals that are flexible and very long. Similarly, in diodontiform mode, thrust is generated by the pectoral fins but they are not in the same level and the same shape as that in mode Rajiform. In amiiform mode, propulsion is obtained by undulations of a long-based dorsal fin. Contrary, in gymnnotiform mode, propulsion is obtained by undulations of a long-based anal fin. In balistiform mode, both the anal and dorsal fins undulate to generate thrust. In labriform mode, thrust is generated by oscillatory movements of the pectoral fins. In tetraodontiform mode, the dorsal and anal fins beat together, either in phase or alternating phase to generate thrust. A figure describes fish swimming modes can be found in [30].

3.1.2. Micro-organisms swimming mechanisms

All the micro swimming mechanics such as flagella, spermatozoa, cilia, and amoeba crate in one way or another a traveling wave, advanced in the opposite direction of the micro organisms locomotion. The swimming mechanics of micro-organisms are divided into flagellar and ciliary swimming.
Flagellar swimming is the simplest swimming method for micro system and is produced by a sinusoidal or helical wave in an elastic tail. In contrast of flagella, cilia beat in asymmetrical fashion i.e. by orienting the cilia parallel to the flow during the recovery stroke much lower drag is produced than when they beat in a more perpendicular orientation during the propulsive stroke [29].

Some piezoelectric miniature robots like swimming fishes are developed in [31-37], where piezoelectric actuators are used for producing the movements of BCF and MPF for miniature robots. The choice between swimming modes in liquid depends on the application expected. For example the design of thunniform swimmers miniature robots is optimized for high speed swimming in calm waters and is not well suited to other actions such as slow swimming, turning maneuvers and rapid acceleration from stationary and turbulent water [30]. Also piezoelectric actuators are used in [38 & 39] for creating the travelling wave needed for the movements of swimming micro organisms.

3.2. Locomotion at the water surface

Locomotion at the water surface is divided into two different locomotion principles: striding on the water surface like water striders and running on the water surface like a basilisk lizard. Water striders take advantage of their size by using the surface tension of water to generate forces in order to step over the surface of water. These forces increase with the depth of the unwetted limb of the water striders [29]. Basilisk lizard have a weight which is larger than the surface tension can support, it takes advantage of the mass density of the water, which exerts a reactive force when running rapidly with its webbed feet [29]. As example we take the water strider miniature robot walking on water describes in [40].

4. Locomotion in air

The movement in air for mobile robots is classified into two groups: active air vehicle and passive air vehicle. The first group is divided into three different locomotion principles: flapping, rotary and fixed wing. The passive air vehicle consists of one locomotion principle, the gliding flight. Like in liquid locomotion, the Reynolds number (Re) is an important parameter in the design of flight vehicles, and it is defined in the same manner. The Re varies linearly with air vehicle weight [41], so miniature air vehicles (MAVs) operate at low Re where the viscous forces dominate. The flapping wing method is the most efficient way for MAVs because it generates the greatest thrust with the same power expended, among the other methods and it is the most used in the field of piezoelectric miniature robots, for this reason, it is the only method described here.

4.1. Flapping wing MAV

Unsteady state flow aerodynamics is obtained in the case of flapping wing MAV, because leading-edge vortices (LEV) are formed during downstroke wing (Fig.4) and are shed at the start of the upstroke and so on. LEV helps to generate a high lift coefficient during flight and according to the movements of wings and wind, forward thrust is generated during downstroke movement and drag is generated during upstroke (Fig.5). As examples for piezoelectric flapping wings MAV, see references [42-46].
References


