Design of a Miniaturized Locomotion System with Variable Mechanical Compliance Based on Amoeboid Movement

T. Kaufhold, V. Böhm, and K. Zimmermann

Abstract—This paper describes a novel biologically inspired locomotion system. The main advantages of amoeboid movement are implemented in a magnetically actuated compliant vibration driven system. The locomotion of the system is based on the periodic deformation of an elastomeric structure including segments with reversible variable mechanical compliance. The movement direction is defined by an asymmetric configuration of the elastomeric structure induced by segments with differing mechanical compliance. The working principle of the system is discussed with the help of modal and transient dynamic analyses. Based on the numerical simulations, two prototypes are developed and verified with experimental tests.

I. INTRODUCTION

TERRESTRIAL locomotion systems are dominated by systems with legs and wheels, but they have a limited field of application [1]. Future robots with high mobility require the use of new, non-conventional locomotion principles. Because of deficits of motion in difficult terrains, the investigation of amoeboid locomotion is of special interest and importance for developing mobile robots. The movement of the amoeba is characterized by cytoplasmic streaming and continuous changing the body shape (Fig. 1).

Three main phases of amoeboid locomotion are: protrusion (extension of selected regions of the body), attachment (connection to the ground), and traction (forward movement of the body) [2]-[4]. For an engineer this principle of locomotion offers a fascinating characteristic: the possibility to combine the function of locomotion and manipulation for systems operating in difficult terrains [5].

In current robotic research, however, trials to adapt amoeboid locomotion are dominated by systems consisting of a large number of elementary locomotor units (systems of type A) representing amoeboid behavior only as a swarm [6], [7]. To avoid the disadvantages of these systems, such as multiple complex construction, and distributed control effort, first studies of amoeboid locomotion systems as single locomotor units (systems of type B) have been recently presented. The locomotion of these systems is based on their deformability. The first group of these systems consists of a conventional cascaded planar set of elements, which are able to change their length and/or their mechanical compliance [8], [9]. In the latter case a global drive provides the change of the element lengths. Shape variability of systems in the second group is based on their intrinsic mechanical compliance as in the biological model [10]-[12]. Possible realization strategies for these systems are (sorted with increasing abstraction):
- internal fluid flow (pressure gradient) in the whole body without/with locally variable mechanical compliance, which induces the deformation of the body (type B/I);
- uniform pressure in the whole body with locally variable mechanical compliance, whereby the local change of compliance causes deformation of the body (type B/II);
- locally differing deformation of a compliant body without/with changing the mechanical compliance (type B/III).

From the technical point of view the most relevant advantage of amoeboid locomotion is due to the large shape variability (I). The primary target of known developments is the adaptation of this property. In the biological model shape variability is based on an intrinsic mechanical compliance (II). The implementation of this property in technical systems is also advantageous, because it allows their simple construction. Further important features are: the locomotion is induced by a single drive mechanism (III), the direction of locomotion is defined by local change of the mechanical compliance (IV) [13].

In the present contribution, a planar miniaturized locomotion system is considered by which these discussed main properties of amoeboid motility mechanism are implemented. The system, belonging to the group B/III, is characterized by a marked flexibility, a simple construction...
and an integrated actuation mechanism.

The paper begins by providing the design of the locomotion system in Section II and a theoretical explanation of the working principle in Section III, followed by experimental results in Section IV. Finally, in Section V conclusions and future development directions are considered.

II. DESIGN OF THE LOCOMOTION SYSTEM

Known miniaturized locomotion systems primarily use electroactive polymers (EAP), shape memory alloys (SMA) [14]-[16] or ionic polymer-metal composites (IPMC) [17]-[18] as actuators or pneumatic/hydraulic drives. They all require large numbers of actuators with partly large time constants. Alternatively, the implementation of magnetic-based actuators in combination with elastomeric materials offers new actuation possibilities for robotic applications [19], [20] as well as amoeboid locomotion systems. This combination allows higher actuation forces as well as an increased deformation range while the response time is being reduced. These robots are actuated by shifting elastomeric structure parts with integrated NdFeB magnets, resulting from a magnetic force. The fast response time of this actuation principle enables the realization of vibration driven systems based on periodic motion of internal masses.

Our goal is the realization of a planar locomotion system with a simple assembly. Therefore, the shape variability of the system is realized by a compliant elastomeric structure, which is divided into three segments with embedded NdFeB magnets in each segment. The elastomeric structure is magnetically coupled with an internal rotary actuator including three magnets, allowing their periodical deformation. The geometry of the system is based on an equilateral triangle. Fig. 2 illustrates basic configuration and actuating mechanism of the robot.

Due to the 3 axes of symmetry the system is able to form large symmetrical systems (combination of 3, 6, 10, and so on, systems by connection of selected corner points). These systems enable advanced manipulation tasks, such as enclosing and subsequent transport of objects.

The deformation of the elastomeric structure can be induced by attractive or repulsive magnetic forces between the magnets in this structure and the magnets housed on the rotor. If all magnets on the rotor have the same radial polarization and all magnets in the elastomeric structure have identical or opposite radial polarization, the system rotates around its center line due to different mass moment of inertias of system parts. To minimize this behavior, an asymmetric polarization configuration of the magnets on the rotor was chosen (Fig. 2).

The locomotion direction of the system is defined by asymmetric mechanical compliance of the elastomeric structure. The mechanical compliance of three segments of the elastomeric structure can be reversibly changed from a compliant to a stiff state. Therefore the “jamming effect” is used [21], by which a transition between a liquid-like and a solid-like state of granular materials occurs. Jamming can be realized with a small change in confining volume of the granular material, e.g. through application of a vacuum [22]. The implementation of this effect is a recently discussed topic in robotic applications with variable mechanical compliance [11], [23].

In our prototype the elastomeric structure has three cavities, which are filled with spherical glass particles. The mechanical compliance of the structure can be changed by changing the volumes of the cavities. To achieve locomotion of the system, an unequal depressurization of the chambers is needed, resulting in an asymmetrical mechanical compliance of the elastomeric structure. The change of compliance is dependent on the particle size of the granular material, and on the magnitude of the applied vacuum for a given geometrical configuration and degree of filling. To study the influence of these factors, a simple experiment was performed. A hollow elastomeric cylinder (outer diameter: 50 mm, length: 35 mm, wall thickness: 1mm, shore hardness: A8), filled with spherical glass particles, was compressed along its longitudinal axis (z-axis) with a force Fz under quasistatic conditions, and thereby the force-deflection curve uz(Fz) was evaluated as a measure for the mechanical compliance by using different particle sizes and vacuum-magnitudes. Selected measurement results are shown in Fig. 3. The compliance uz/Fz of the cylinder shows a significant dependence of the applied vacuum and of the particle sizes: at a given particle size a magnification of the compliance up to forty times can be detected by applying a vacuum of 0.33 bar. Furthermore, by using larger particles a generally higher stiffness can be reached.

In recent works the use of magneto-sensitive elastomeric materials in robotic applications has also been discussed [24]. The replacement of the magnets in the elastomeric
structure is conceivable, but was not considered because of the desired simplicity of the system.

III. THEORETICAL CONSIDERATIONS

A. Modeling aspects

Due to the mechanical compliance of the prototype, the modes of vibration are complex and the locomotion performance of the system is highly dependent on the driving frequency. To analyze this specific behavior we focus on the description of the mechanical point of view. According to the specific task, geometric nonlinear transient structural finite element analyses were carried out with the software package ANSYS v12.1.

In the FE model, rigid beam elements are used for the frame and connection elements (Fig. 4). The elastomeric structure is modeled with elastic beam elements. For these elements, a linear ideal visco-elastic material model is assumed with Young’s Modulus \( E = 1 \) MPa, and Rayleigh \( \beta \)-damping coefficient \( \beta = 0.002 \). For simplicity reasons, masses are concentrated and applied with mass point elements at the nodes of the system. The connections between the beam elements are realized with torsional spring elements. For these elements, maximum rotation angles of 10° were defined. The variable mechanical compliance of the three segments (A, B, and C) of the elastomeric structure is implemented with variable torsional stiffnesses for spring elements at \( r = r_1 \). The spring rates were varied between \( c_2 = 25 \text{ Nmm/deg} \) (segment is compliant) and 40,000 Nmm/deg (segment is stiff).

<table>
<thead>
<tr>
<th>p - pressure</th>
<th>d - diameter of glass particles</th>
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<td>0.33 bar</td>
<td>d = 40-80 ( \mu )m</td>
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<td>0.33 bar</td>
<td>d = 70-110 ( \mu )m</td>
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<td>0.33 bar</td>
<td>d = 105-210 ( \mu )m</td>
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Fig. 3. Force-deflection curves of the elastomeric cylinder filled with spherical glass particles of different sizes: for atmospheric pressure (a), and vacuum of 0.33 bar (b); and at different pressures for a chosen particle size (c); Direction of the applied force and measured displacement: z-direction (axial).

The isotropic Coulomb friction model is implemented between the locomotion system (nodes at \( r = r_3 \), and \( r = r_1 \), s. Fig. 4) and the supporting plane with equal static and kinetic friction coefficients.

In our simplified model, the magnetic forces between the NdFeB magnets of the rotor and embedded NdFeB magnets of the elastomeric structure are concentrated and applied on the corresponding mass points of the system (white arrows in Fig. 4). The directions of the magnetic forces have been adjusted according to the relative position of the magnetic structure parts and are actualized continuously during the solution. Due to a simple model, the movement of the rotor was considered with a simple force function as depicted in Fig. 5, with a maximal acting force magnitude of \( F = 0.05 \) N, and with variable driving frequency “f”. One period of the force function corresponds to one complete rotation of the rotor (periodic time: \( T = 1/f \)).

Fig. 5. The applied force function used in the simulations.

B. Results of the simulations

For a first specification of the dynamic system performance, modal analyses, using the Block Lanczos solver, are performed. Due to the specific real boundary conditions and system parameters, the system was fixed only normal to the x-y-plane. The variability of the mechanical compliance of the elastomeric structure enables the active control of the natural frequencies of the system. To show
this property, analyses with a single stiff segment (segment A) and with two stiff segments (segments A and C) were carried out. The calculated natural frequencies in both cases differ to each other and are in the lower frequency range because of the significant mechanical compliance. Two characteristic types of eigenmodes were found (Fig. 6): longitudinal oscillations along the symmetry axis with respect to the stiff segment(s) and rotational oscillations around the z-axis (center of rotation: node at \( r=r_2 \) or \( r=0 \)).

Fig. 6. Selected mode shapes of the system with one stiff segment (a), (c) and with two stiff segments (b), (d).

These properties are favorable from the perspective of locomotion of the system:
- because of large material-specific damping, the operation of the system is aimed at low driving frequencies,
- the presence of different mode shapes in the lower frequency range can be used to realize locomotion of the system in different directions of the system at different driving frequencies.

To describe the movement of the system dependent on the driving frequency, transient dynamic geometric nonlinear analyses, including all contact conditions and Coulomb-Friction between the elastomeric structure and ground, were carried out (Fig. 4). In the analyses, the driving frequency, the number of stiff segments (1 or 2), and the compliance of the segments with variable compliance were varied. In the simulations the path of the center of gravity (Point M in Fig. 4), the outer corner nodes and the velocity of the system were evaluated. Fig. 7 show selected results of these simulations.

The numerical simulations prove the locomotion of the system. Furthermore, the following important results were obtained:
- the locomotion direction can be set by changing the stiffness of the segments with variable compliance (for example the change of the stiff segments from A and B to A and C during the locomotion),
- for a given configuration with 1 or 2 stiff segment(s) the locomotion direction can also be influenced only by changing the driving frequency and/or the magnitude of the applied forces,
- the system moves uniaxial or along a curved path in dependence of the control parameters (Fig. 7),
- for the given parameters a maximal average velocity of 0.24 mm/s of the system at \( f=5/3 \) Hz was estimated (\( F=0.05 \) N, No. of stiff segments: 2).

Fig. 7. Path of the nodes in the x-y-plane after 100 periods for different driving frequencies: (a) \( f=1.25 \) Hz, (b) \( f=1.67 \) Hz, (c) \( f=2.08 \) Hz; (d): displacement components of the mid-point M (\( u_{xM} \), \( u_{yM} \)) in the x-y-plane vs. time for \( f=1.67 \) Hz (\( t=0 \) s was chosen arbitrarily).

IV. EXPERIMENTAL EVALUATION

Based on the simulations, two prototypes were developed and built. These prototypes differ in the assembly of the silicone elastomer body and connection elements. Fig. 8 shows the CAD models in an exploded view. As assumed in the simulations, these systems are based on the periodic asymmetric deformation of a compliant body. The periodic deformation is magnetically induced only by one central rotary drive. The direction of locomotion is defined by changing the mechanical compliance of selected segments of the elastomeric structure using the jamming effect as discussed in Section II.

The developed prototype 1 (Fig. 8 (a) and (c),...
diameter: 67.5 mm, height: 21.5 mm, total mass: 18.4 g) is driven by a single brushless DC-Gearmotor (“penny-motor technology” series 1309 004 BH, mass: 2.8 g, diameter: 12.5 mm, height: 10.8 mm) with a torque of 5 Nmm (continuous operation) at an output speed of 111 rpm. The motor is driven by a speed controller (Faulhaber speed controller series SC 1801) which has a PWM signal output with a nominal voltage $U_{\text{nom}} = 4$ V. Attached to the shaft of the motor are six permanent magnets (material: NdFeB, dimensions: 5 x 5 x 2 mm, $B_{\text{rem}}$: 1.35 T) in pairs of two.

Moreover, permanent magnets are installed in the middle of the structure can be locally changed when evacuating the air. The compliant body (mass: 4.4 g) is made of condensation curing silicone elastomer (shore hardness: A8) and is divided into three chambers which are filled with spherical glass particles (diameter: 150-210 µm, filling factor: 60 %). The chambers have hose connections (outer diameter: 1 mm, inner diameter: 0.5 mm, material: PVC) by which the compliance of the segments of the elastomeric structure can be locally changed when evacuating the air. Moreover, permanent magnets are installed in the middle of each side (Fig. 8). The motor is enclosed by, and the silicone elastomer body is attached to, a plastic material skeleton (ABS-Copolymer, density: 1.04 g/cm³) manufactured with rapid prototyping. Between the prototype and the ground, the measured coefficient of static friction is $\mu_s=0.15$ and the coefficient of kinetic friction is $\mu_k=0.077$. Prototype 2 has a total mass of 19.4 g while the silicone elastomer body has a share of 4.6 g. The filled in glass particles also have a diameter of 150-210 µm.

Because of the mainly equal shape, assembly, and dimensions of both prototypes, only snapshots of prototype 1 are depicted in Fig. 9.

The locomotion of the prototypes was recorded with a high speed camera (model: HCC-1000; manufacturer: Vosskühler GmbH; recording parameter: 31.83 FPS). The videos were analyzed using Matlab R2009b performing a contour detection and a mid-point detection using image transformations and morphological operations.

Fig. 8. Exploded view of prototype 1 (a) and 2 (b); (c) and (d): bottom view of the prototypes with silicone elastomer body cut open (1- motor, 2- housing, 3- rotor, 4- magnets, 5- plastic skeleton, 6- elastomer body top, 7- glass particles, 8- elastomer body bottom).

Fig. 9. Snapshots of the assembled prototype 1.

The locomotion system and displacement of the mid-point (x-direction) for 2 stiff segments (a), (c) and 1 stiff segment (b), (d); (time interval for (a), (b): 27 s, t=0 s was chosen arbitrarily).
Selected results for actuation parameters: 167 rpm output speed of the motor (direction: clockwise) and 97% vacuum connected to the chambers of prototype 2, with two configurations (1 stiff segment, 2 stiff segments) are shown in Fig. 10. The experiments have shown that locomotion in the plain is possible with both prototypes. In accordance with the theoretical analyses, the velocity as well as the locomotion direction of the system depends on the magnitude of the vacuum, on the number of depressurized chambers, and on the speed of the motor.

For prototype 2, maximum average speeds of 1.96 mm/s (1 stiff element, Fig. 10 (b), (d)) and 2.17 mm/s (2 stiff elements, Fig. 10 (a), (c)) were determined (rotor speed 167 rpm). For prototype 1 a maximum average speed of 2.65 mm/s, also with 2 stiff segments, was measured.

V. CONCLUSIONS AND FUTURE DEVELOPMENT

This paper presents a new concept for vibration-driven miniaturized compliant locomotion systems based on amoeboid movement. Therefore, the main advantages and properties of amoeboid movement were considered and partly implemented in a developed prototype. The planar movement of the system is achieved by an asymmetric periodic deformation of a compliant structure, including segments with variable mechanical compliance.

In contrast to the biological object, the level of abstraction of the technical system is high, resulting from a desired simple design. The main idea by the design of the system was the biological inspired implementation of the variable mechanical compliance. The local change of the compliance during locomotion is used to change the movement direction.

Future work is addressed to increase shape variability of the system, determine optimal control strategies, and investigations on the behavior of the robot at loose/compliant ground and in liquid media. We focus also on systems with prestressed compliant segments and on fully compliant prestressed structures to increase the movement performance.

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