9. Hoye N., Appel E.C., Cuiuri D., Li H. Characterisation of metal deposition during additive manufacturing of Ti-6Al-4V by arc-wire methods // Faculty of Engineering and Information Sciences – Papers. – 2013. – Vol. 24. – P. 1015-1023.

10. Cammett J.T. The effect of shot peening coverage on residual stress. Cold work, and fatigue in a nickel-base superalloy // Proceedings of the International Conference on Shot Peening, Sept. 6-9, 2005, Paris, France. – Paris, 2005. – P. 1-5.

11. Yildirim B. Simulation and Modeling of Residual Stresses due to Overlay Welding // Lehigh University, USA, 1998. – 30 p.

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BRISTLEBOTS IN SWARM ROBOTICS – NEW APPROACHES IN MODELING AND AGENT DEVELOPMENT

Bristlebots are vibration-driven mobile robots. They are characterized by small size, high speed, simple design and low costs of production and application, which are advantageous qualities for agents of swarm robotic systems. In this paper, new approaches in modeling and development of swarm agents are given. It is shown that a simple mass point model can be used to simulate the motion behavior of a bristlebot as complex as necessary for swarm studies. A robot prototype is presented, which has on-board everything needed as a robotic agent. The results of simulations and experiments are presented and compared.

Introduction

Swarm robotics is a recent trend in mobile robotics. It focuses on the study and development of robotic systems comprising a great number of agents that cooperate in order to fulfill tasks. Especially in the vast fields of inspection, communication and transportation technology, swarm robotic solutions can achieve admirable results. Biological examples of swarms can give an insight into the amazing potential lying in the cooperation of individuals [1]. Inspired by insects that live in colonies, researches try to create miniaturized artificial swarm robotic systems [2 - 8]. For this reason, simple, small and light hardware platforms with low power consumption are needed. An important part of a mobile robot is its locomotion module. It creates actuation forces to accelerate the robot. Locomotion modules based on bristlebots are simple and reliable solutions [7 - 13].

The locomotion of bristlebots is driven by the vibration of internal masses. The periodic excitation is transformed into directed motion due to asymmetric friction properties achieved by bristles. The working principle can be divided into two groups – 1st: short, stiff bristles or spikes which can mechanically interlock with a surface; and – 2nd: long, elastic bristles which can be deformed and create the asymmetric friction properties caused by periodic normal forces. Both different locomotion schemes are studied in detail in [9].

To the authors, the first publication concerning bristlebots is known in the youth journal “Юный Техник” in 1977 [14]. A bristlebot with the ability to find light sources autonomously was presented in the same journal one year later [15]. Bristlebots have its renaissance over the last ten years, e. g. as self-made toys constructed from a tooth brush, a button cell battery and a vibration motor form a cell phone or pager. The idea to use bristlebots in microrobot teams is presented in [7], [8]. The robots in [8] are not equipped with additional electronics like it is usual for swarm robots. The only form of swarm intelligence, communication or interaction between the individuals is the mechanical interaction due to collisions with borders of a test area and between the robots. Swarm behavior can be observed, if the number of robots per area exceeds a critical amount.

The aim of this paper is to give approaches to modeling and agent development in swarm robotics. The presented robot prototype is based on bristlebots – a simple, robust and cheap locomotion technology. The proposed model comprises the main influences from geometry and motor control to the two-dimensional locomotion system and may be used as basis for complex simulations of homogenous or heterogeneous swarms with bristlebot-based agents.

Mechanical model and equations of motion

For swarm simulations the underlying mechanical model of an agent should be as simple as possible, but should comprise the dominant locomotion mechanisms. Analyses of the motion behavior of bristlebots in [9 - 12] show that the locomotion is determined by periodic actuation forces and non-symmetric friction forces. The proposed mass point model is presented in Fig. 1.

The system is composed by two mass points P_1 and P_2, which carry masses m_1 and m_2, respectively. They are connected by a massless bar of the length $\overline{CP_1}+\overline{CP_2}=b_1+b_2$. Two Cartesian coordinate systems are introduced: a fixed reference frame with the unit vectors $\left(\vec{e}_x,\vec{e}_y,\vec{e}_z\right)$, and a body-attached frame with $\left(\vec{E}_x,\vec{E}_y,\vec{E}_z\right)$, which is situated in the center of mass $C(x_c,y_c,z_c)$. The motion of the system is limited to the plane $\left(\vec{e}_x,\vec{e}_y\right)$, therefore $\vec{e}_z=\vec{E}_z$. The number of degrees of freedom equals three. With the angle $\angle(\vec{e}_x,\vec{E}_x)=\theta$, it follows

$$\begin{aligned} \vec{e}_x &= cos\div\vec{E}_x - sin\div\vec{E}_y, & \vec{E}_x &= cos\div\vec{e}_x + sin\div\vec{e}_y, \\ \vec{e}_y &= sin\div\vec{E}_x + cos\div\vec{E}_y, & \vec{E}_y &= -sin\div\vec{e}_x + cos\div\vec{e}_y. \end{aligned} \tag{1}$$

The vibration motor generates the forces $\vec{A}_y$ and $\vec{A}_z$ at the point A. They are determined by the motion of the mass m_e on a circular orbit with a radius e and angular velocity $\dot{\varphi}=\Omega$ in the plane $\left(\vec{E}_y,\vec{E}_z\right)$:

$$\begin{aligned} \vec{A}_y &= -m_e e\Omega^2 cos\left(\Omega t\right)\vec{E}_y, \\ \vec{A}_z &= -\left[m_e g - m_e e\Omega^2 sin\left(\Omega t\right)\right]\vec{E}_z. \end{aligned} \tag{2}$$

At the points P_1 and P_2, normal forces $\vec{N}_1,\vec{N}_2$, Coulomb dry friction forces $\vec{F}_{R1},\vec{F}_{R2}$ and actuation forces $\vec{F}_{A1},\vec{F}_{A2}$ are applied. The actuation forces are modeling the periodic forward forces produced by the elastic bristles due to the excitation of the motor:

$$\vec{F}_{A1}=F_{A1}sin\left(\Omega t\right)\vec{E}_x, \qquad \vec{F}_{A2}=F_{A2}sin\left(\Omega t\right)\vec{E}_x. \tag{3}$$

As the actuation forces of bristles are developed by the frictional contact between the robot and ground, their magnitudes F_{A1} and F_{A2} may not exceed the friction forces in backward direction. The normal forces $\vec{N}_1=N_1\vec{E}_z$ and $\vec{N}_2=N_2\vec{E}_z$ can be calculated using the equilibrium of forces in $\vec{e}_z$-direction and the equilibrium of moments about $\vec{E}_y$:

$$\begin{aligned} 0 &= N_1+N_2+A_z-\left(m_1+m_2\right)g, \\ 0 &= -b_1N_1+b_2N_2+aA_z. \end{aligned} \tag{4}$$

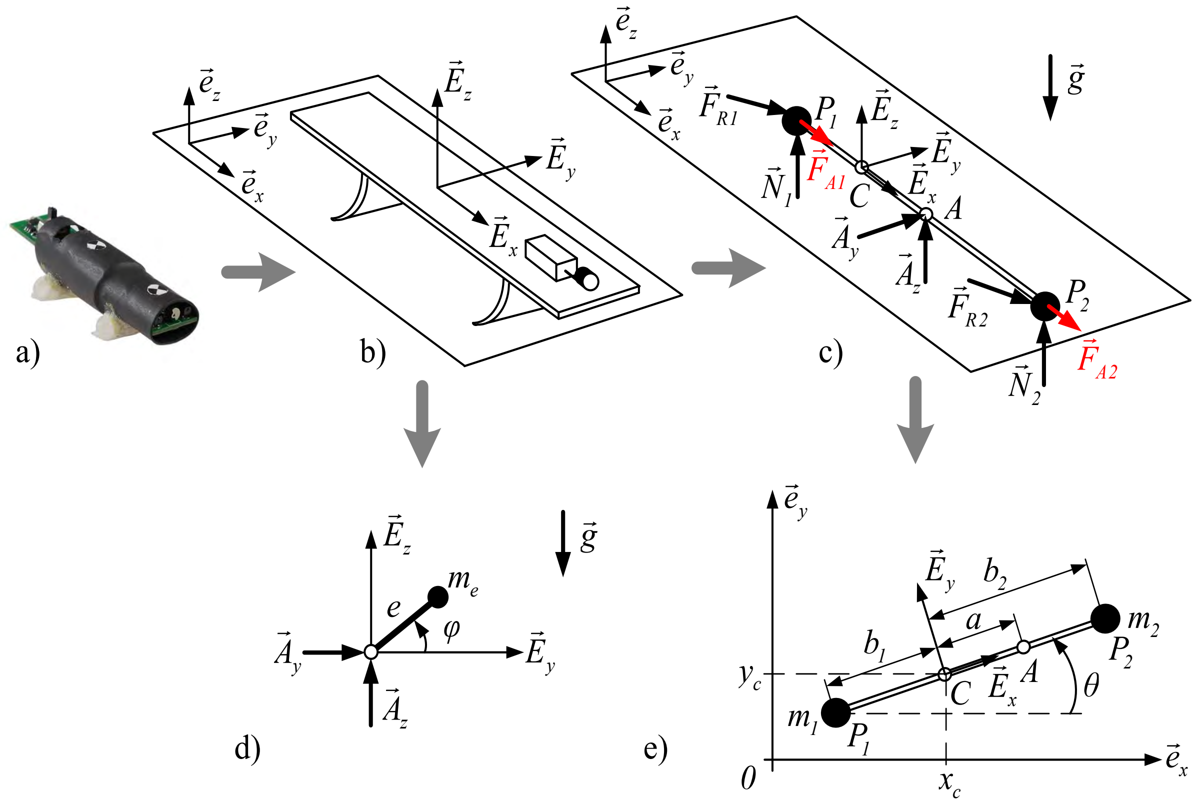

Fig. 1. Modeling of the robot: a – Robot prototype; b – Schematic robot; c – Robot model with forces; d – Motor model; e – Geometry and coordinates

With $\overline{CA} = a$, it follows:

$$N_1 = \frac{b_2}{b_1 + b_2}(m_1 + m_2)g + \frac{b_2 - a}{b_1 + b_2}\left[m_e g + m_e e \Omega^2 \sin(\Omega t)\right];$$
$$N_2 = \frac{b_1}{b_1 + b_2}(m_1 + m_2)g + \frac{b_1 + a}{b_1 + b_2}\left[m_e g + m_e e \Omega^2 \sin(\Omega t)\right]. \tag{5}$$

In order to fulfill the condition of constant contact, it is needed that $N_1 \geq 0$ and $N_2 \geq 0$. To obtain the friction forces

$$\vec{F}_{R1} = -\mu |N_1| \frac{\dot{\vec{r}}_1}{|\dot{\vec{r}}_1|}, \qquad \vec{F}_{R2} = -\mu |N_2| \frac{\dot{\vec{r}}_2}{|\dot{\vec{r}}_2|}, \tag{6}$$

the velocities of P_1 and P_2 are determined:

$$\dot{\vec{r}}_1 = \dot{x}_1 \vec{e}_x + \dot{y}_1 \vec{e}_y = (\dot{x}_c + b_1 \div sin \div)\vec{e}_x + (\dot{y}_c - b_1 \div cos \div)\vec{e}_y,$$
$$\dot{\vec{r}}_2 = \dot{x}_2 \vec{e}_x + \dot{y}_2 \vec{e}_y = (\dot{x}_c - b_2 \div sin \div)\vec{e}_x + (\dot{y}_c + b_2 \div cos \div)\vec{e}_y. \tag{7}$$

Absolute values of the velocities are $|\dot{\vec{r}}_1| = \sqrt{(\dot{x}_1)^2 + (\dot{y}_1)^2} \neq 0$ and $|\dot{\vec{r}}_2| = \sqrt{(\dot{x}_2)^2 + (\dot{y}_2)^2} \neq 0$. The principle of linear momentum $M\ddot{\vec{r}} = \sum \vec{F}$, where $M = m_1 + m_2 + m_e$ and $\ddot{\vec{r}} = \ddot{x}_c\vec{e}_x + \ddot{y}_c\vec{e}_y$, can be written in two scalar equations on the fixed reference frame $(\vec{e}_x, \vec{e}_y, \vec{e}_z)$:

$$M\ddot{x}_c = -\ldots|N_1|\frac{\dot{x}_1}{|\dot{\vec{r}}_1|} - \ldots|N_2|\frac{\dot{x}_2}{|\dot{\vec{r}}_2|} + m_e e\Omega^2 \cos(\Omega t)\sin\div + (F_{A1} + F_{A2})\sin(\Omega t)\cos\div, \tag{8}$$

$$M\ddot{y}_c = -\ldots|N_1|\frac{\dot{y}_1}{|\dot{\vec{r}}_1|} - \ldots|N_2|\frac{\dot{y}_2}{|\dot{\vec{r}}_2|} - m_e e\Omega^2 \cos(\Omega t)\cos\div + (F_{A1} + F_{A2})\sin(\Omega t)\sin\div. \tag{9}$$

The principle of angular momentum $\dot{\vec{D}}_C = \sum \vec{M}_C$ is applied in the center of mass C with $J = m_1 b_1^2 + m_2 b_2^2 + m_e a^2$ and $\dot{\vec{D}}_C = J\ddot{\theta}\vec{E}_z$:

$$J\div = -a\,m_e e\Omega^2 \cos(\Omega t) - b_1\ldots|N_1|\frac{1}{|\dot{\vec{r}}_1|}(\dot{x}_1 \sin\div - \dot{y}_1 \cos\div) - b_2\ldots|N_2|\frac{1}{|\dot{\vec{r}}_2|}(\dot{x}_2 \sin\div - \dot{y}_2 \cos\div). \tag{10}$$

Simulation

To analyze the presented model, the equations of motion are numerically integrated in MATLAB/Simulink. The values of the parameters, which refer to the prototype presented in Fig. 1, are given in Table 1. It should be mentioned that the parameter range is limited by the condition of constant contact: $N_1 \geq 0$ and $N_2 \geq 0$ discussed previously. Some results of the simulations are presented in Fig. 2. It shows trajectories of the points P_1, P_2 and C for different values of parameters. It may be seen that the robot model moves on a curved orbit. The radius of the trajectory and the velocity depend on the rotational speed of the motor Ω . The turning direction of the model can be controlled by the sign of Ω . The position of the mass m_e relative to the center of mass C of the overall system is labeled with a. The influence of a to the orbit due to the produced torque is also presented in Fig. 2. It is obvious that the increasing overall mass $M = m_1 + m_2 + m_e$ reduces the velocity. Moreover, the system moves faster for a small friction coefficient μ.

Model parameters used in the simulations

Model geometry	b_1	15 mm	b_2	15 mm	a	33 mm
Mass distribution	m_1	5 g	m_2	5 g	J	2.5 kg mm²
Motor parameters	m_e	0.3 g	e	0.2 mm	Ω	-6000 rpm
Environment	g	9.81 m/s²	μ	0.05	t	0 .. 10 s
Actuation forces	F_{A1}	0.0624 N	F_{A2}	0.0624 N		

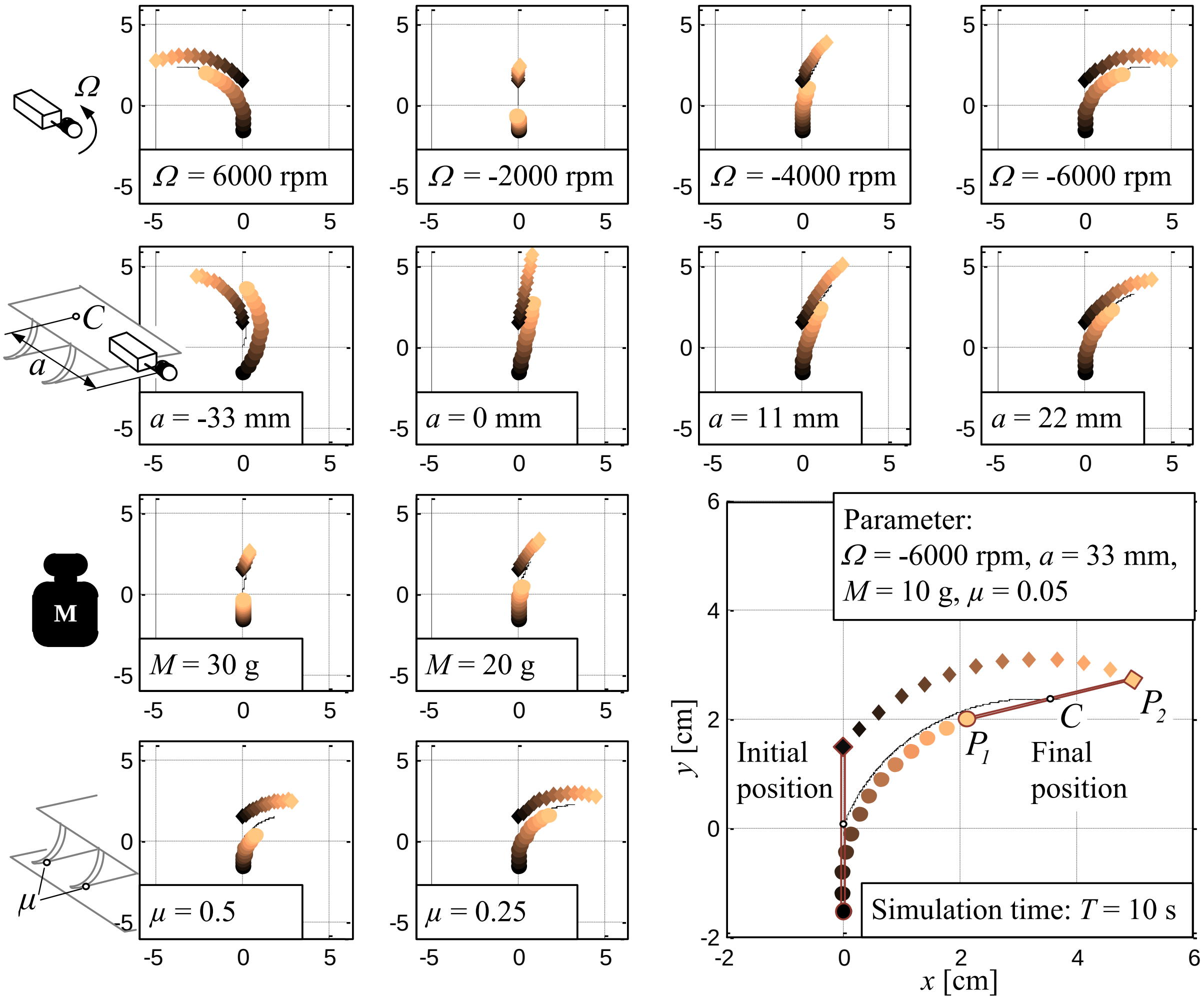

Fig. 2. Numerical parameter study: trajectories of the points P_1, P_2 and C for different values of parameters

Prototype

The developed swarm argent prototype is presented in Fig. 3. It is a bristlebot equipped with additional electronics for programming, autonomous locomotion and communication. From the mechanical point of view, the robot consists of a rigid main body with a total mass M = 10 g, an internal rotating mass point m_e = 0.3 g and two rows of elastic bristles made from foam plastics. The rows are attached to an exchangeable chassis which allows the use of bristle systems with different characteristics. Two markers on the chassis are needed for the optical motion tracking and could be used for automatic locomotion control. The electronic system of the robot consists of a conductor board, an actuation system (motor and motor driver), a power management (battery, voltage regulators), a communication and sensing system (upward and peer-to-peer communication) and a microprocessor.

An Atmega328P microprocessor is used. It has sufficient resources and peripherals to control the system. Due to its application in the well-known Arduino boards, the system can be programmed and expanded over Arduino sketch file programming. The DC vibration motor is controlled using an H-bridge for the rotation direction and pulse-width modulation for the value of angular speed. A Li-ion battery is used with a capacity of 100 mAh. For the communication with the master host (Windows PC), the IrDA technology is selected due to its price, robustness and simplicity. Custom infrared (IR) is used for the communication between the agents (peer-to-peer). The IR wavelength bandwidth does not interfere with the IrDA spectrum. Each agent will have an IR transmitter on the back and two IR receivers at the front. It can be used for different tasks, e. g. following a trail or finding IR sources. Similar to the chemical “leaving a trail”-methods of ants, the robot agents can follow each other.

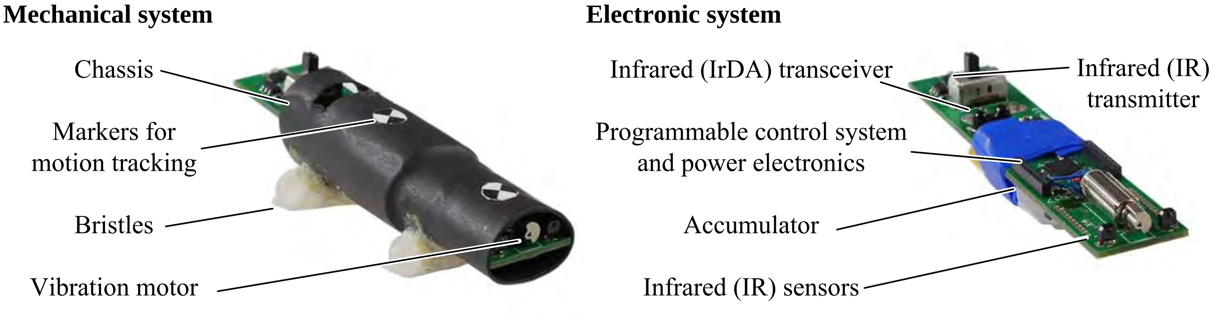

Fig. 3. Prototype of a bristlebot swarm agent:
a – Mechanical system; b – Electronic system

Experiments on locomotion

The experiments on locomotion are performed tracking the markers on a video. Depending on the rotation direction and speed of the motor, different trajectories are observed. Fig. 4 presents motion trajectories of the prototype for different rotational speeds and signs of rotation. The mean value of ten repetitions of the experiments and the root mean square deviation of the measured final position are plotted. As predicted by the simulations, the robot moves always on a curved orbit. By increasing the motor speed, the prototype can move faster and the radius of the trajectory decreases. Of special interest that the motion direction of the robot inverts for high rotational speed (Ω > 12000 rpm) due to resonance effects. As stated in [16] and [17], resonance behavior can be used to control the motion direction of vibration-driven locomotion systems by the excitation frequency.

Using the electronic control system, the robot's way in the *xy*-plane can be combined from a number of curved orbits.

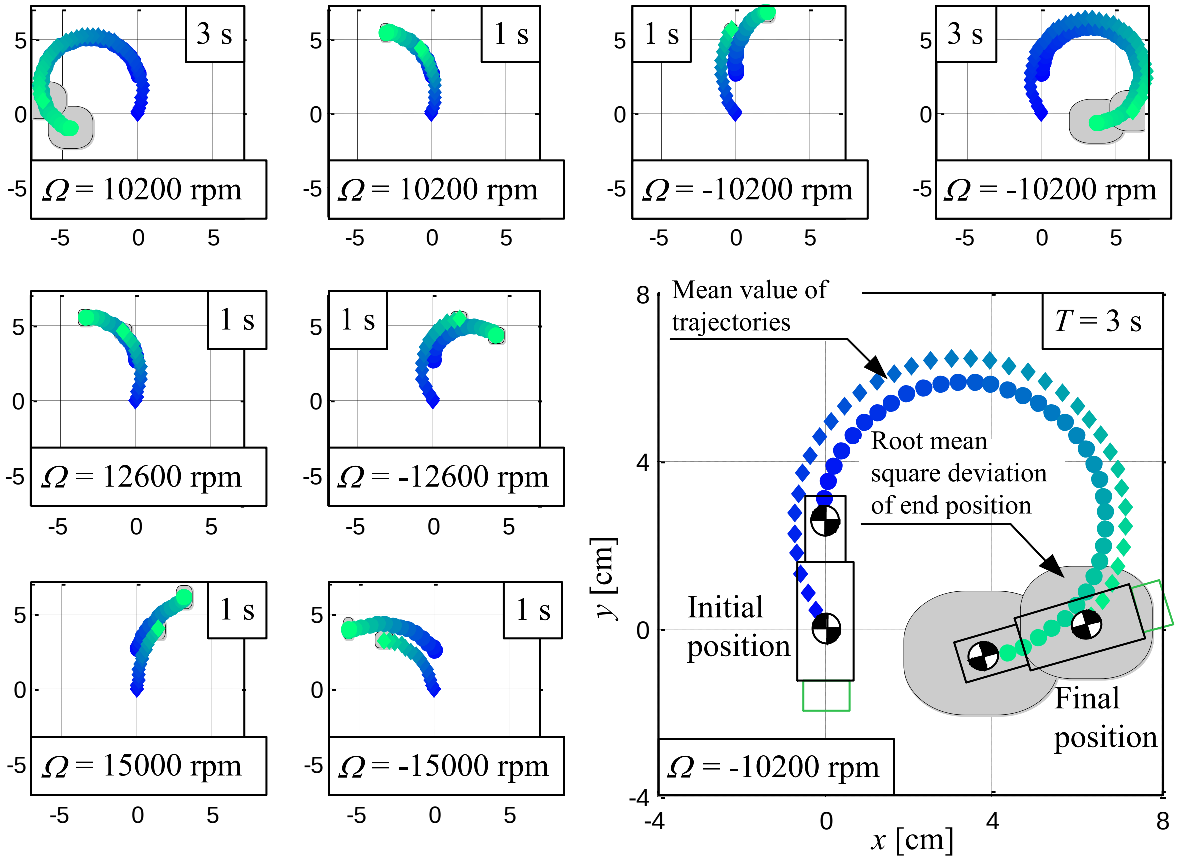

Fig. 4. Experimental parameter study: trajectories of the markers for different rotation speeds Ω and motion times T

Conclusions and outlook

In this paper, a swarm robot agent is presented. The system is inspired by bristlebots. The locomotion can be controlled by rotational speed and rotation direction of the vibration motor. The electronic system of the agent allows autonomous and programmed locomotion. Equipped with a microprocessor, IR receivers and an IR transmitter, it is prepared for an agent-to-agent communication which can be used to achieve swarm behavior. Furthermore, a mechanical model of a single robot is presented. Numerical examples show that it can be used to simulate the locomotion of swarm agents like presented. Due to its simplicity, it has the potential to be used as a subsystem for swarm models. The future work should be connected with the realization of a robotic swarm based on the agent. The proposed model can be used as a basis for complex swarm simulation.

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REFERENCES

1. Bonabeu, E., Dorigo M., Theraulaz G. Swarm Intelligence: From Natural to Artificial Systems. – New York: Oxford University Press, 1999.

2. Flexible Microrobotic System MINIMAN: Design, Actuation Principle and Control / S. Fahlbusch, S. Fatikow, J. Seyfreid, A. Buerkle // Proceedings of IEEE/ASME AIM. – 1999. P. – 156–161.

3. Integrated Electronics for a 1cm3 Robot for Micro and Nanomanipulation Applications: MiCRoN / R. Casanova, A. Saiz-Vela, A. Arbat, J. Colomer, P. Miribel, A. Dieguez, M. Puig, J. Samitier // Proceedings of IEEE/RAS BioRob. – 2006. P. – 13–18.

4. Woern H., Szymanski M., Seyfreid J. The I-SWARM project // Proceedings of IEEE RO-MAN. – 2006. – P. 492–496.

5. Kilobot: A Low Cost Robot with Scalable Operations Designed for Collective Behaviors/ M. Rubenstein, C. Ahler, N. Hoff, A. Cabrera, R. Nagpal // Robotics and Autonomous Systems. – 2014. – № 62 (2). – P. 966–975.

6. Development of an autonomous micro robot for swarm robotics / F. Arvin, J. C. Murray, L. Shi, C. Zhang // Proceedings of IEEE ICMA. – 2014. – P. 635–640.

7. L. Let’s All Pull Together: Principles for Sharing Large Loads in Microrobot Teams / D. L. Christensen, S. A. Suresh, K. Hahm, M. R. Cutkosky // IEEE Robotics and Automation Letters. – 2016. – №. 1 (2). – P. 1089–1096.

8. Giomi L., Hawley-Weld N., Mahadevan L. Swarming, swirling and stasis in sequestered bristle-bots // Proceedings of the Royal Society A. – 2013. – № 469. – P. 1–21.

9. On the Mechanics of Bristle-Bots – Modeling, Simulation and Experiments / F. Becker, S. Börner, V. Lysenko, I. Zeidis, K. Zimmermann // Proceedings of ISR/ROBOTIK. – 2014. – P. 15–20.

10. Ioi K. A Mobile Micro-Robot using Centrifugal Forces // Proceedings of IEEE/ASME AIM. – 1999. – P. 736–741.

11. Spy Bristle Bot – A Vibration-driven Robot For The Inspection of Pipelines / F. Becker, S. Börner, T. Kästner, V. Lysenko, I. Zeidis, K. Zimmermann // Proceedings of 58th IWK Ilmenau, 2014.

12. Majewski T., Szwedowicz D. Behavior of the Robot with Vibratory Excitation // Proc. of MUSME. 2015. Mechanisms and Machine Science. – 2015. – № 25. – P. 67–74.

13. Han Y., Marvi H., Sitti M. Fiberbot: A Miniature Crawling Robot Using a Directional Fibrillar Pad // Proceedings of IEEE ICRA. – 2015. – P. 3122–3127.

14. Сенюткин А. Виброходы // Юный Техник. – 1977. – № 6. – P. 65–67.

15. Борисов Ю. Виброход идёт на свет // Юный техник. – 1978. – № 4. – P. 72–73.

16. Zimmermann K., Zeidis I., Behn C. Mechanics of Terrestrial Locomotion // Springer. – Berlin, 2009.

17. Becker F. Zur Mechanik vibrationsgetriebener Roboter für terrestrische und aquatische Lokomotion // Phd thesis. Universitätsverlag Ilmenau, 2015.

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HUMAN-ROBOT INTERACTION – KEY RESEARCH PROBLEMS

Research on Human-Robot Interaction (HRI) is devoted to the development of the methods delivering the robots which are collaborating and interacting with humans in an effective and natural way. This field receives considerable attention in the robotics research