Towards Electron-Beam-Driven Soft / Polymer Fiber Microrobotics for Vacuum Conditions

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Abstract. The possibility of creating vacuum robotics based on the polymer structures irradiated by an electron beam, in particular, polymer fibers, which provide high functional flexibility and a variety of states, is discussed. The possibility of using polymer fibers as different types of MEMS-like electromechanical elements is demonstrated - from elastic cantilevers to springs that change their state under the electron beam. Experimentally proved the presence of different functional types of fibers, correlating with their thickness, as well as the phenomenon of the fiber break. A number of exotic forms of dynamics have been demonstrated and a method for their detection has been developed using 2D Fourier spectra, integral spatial characteristics, time resolved correlograms and wavelet transforms (visualized as the scaleograms / scalograms). Access barcodes for the full video records of the corresponding experiments are provided.

Introduction

Vacuum, ultra-high vacuum and cryovacuum microrobotics are at the frontiers of the modern mechatronics development. Design of the robot machine for ITER (International Thermonuclear Experimental Reactor) vacuum vessel assembly and maintenance assumes that the robot can operate in vacuum vessel conditions [1-6]. Recently, similar work is underway in China aimed at the design of a fusion reactor CFETR (Chinese Fusion Engineering Test Reactor [7]). The authors of the last cited work [7] emphasize that "the assembly of vacuum vessel (VV) is a vital task for the fusion reactor" and any violation of the technological conditions during the VV assembly or operation is an emergency situation. A similar situation is observed in microelectronics, where the robots for use in ultrahigh vacuum are also useful for wafer-transfer manipulations [8-12], and the disruption of the processing modes leads to multimillion-dollar losses from any defective batch of the mass chips. Accordingly, the controllability of robots in vacuum conditions is of high importance. In the case of vacuum robots for microelectronics, the most widely used are magnetic transmission technology or coaxial twin-shaft magnetic fluid seals applied in vacuum wafer-handling robots [13]. Operation stability at the macroscales is achieved by controlling the magnetic field since magnetic switching for microrobotics is a much more difficult task. The problem of position-sensitive control in vacuum microrobotics is still poorly developed.

At the same time, for microrobotic tasks that do not allow working with cables (in contrast to macroscales as in a cable-driven robotized arm for tracking in TOKAMAK vacuum vessels [14]), the size of which may exceed the cross-sections of the actuated structures, it is advisable to create conditions for the contactless signal transduction at the scales from the order of hundreds of nanometers up to several microns.

For a “cable” approach application, another method of solving the above problem is possible – combining a vacuum “microcable” and an extended micromanipulator in a single structure.

However, the question of supplying a signal to the input unit (sensor and actuator) remains open. In this case, it is possible to propose the use of the antenna properties of the cable to receive the input signal, especially for transmission of the signal to the cable using a focused microbeam corresponding in size at the projection point to the size of the antenna and the actuated structure. The use of radio frequency signals for actuation at these scales is not possible, since the “antenna” dimensions are much smaller than the wavelength (excluding the terahertz range, where the physics of metamaterials operates).

Therefore, it is proposed to use the excitation of “antennas” integrated with the “microcables” for signal transduction and fibrillar or flexible actuators (powered by the energy of the signal supplied to the antenna), by the focused electron microbeam of the medium energy that does not disrupt the structure, but provides kinematics of its movement. Application of metal wire structures for these purposes is not suitable both due to the metallographic reasons and their fractographic consequences, and due to the high densities of the beam energy flux, which must be supported to the material in order to ensure its deformation and movement of the metal wires (this task is more close to the electron beam melting than to the problem of the material deformation under the electron beam).

Therefore, perhaps the only rational approach is the use of polymer / fibrillar-composite materials, the extended components of which can serve both as an antenna and an actuator, and also possess simple cable or membrane-mimetic properties, which ensure the signal transduction along the surface / “membrane” of the actuators [15]. It is noteworthy that despite the vacuum robotics history starting from the last quarter of the XX century [16-18], the above approach integrating all functions in a single structure in accordance with TRIZ requirements, has not been found in the literature. This indicates the novelty and promising nature of the approach proposed and opens the prospects of its wide practical application.

Materials and Methods

Polyhydroxybutyrate (PHB) 16F was purchased from BIOMER Company and used as received. PHB molding solutions with a PHB concentration of 7 wt% in chloroform were used to obtain ultra-thin fibers by electrospinning (ESP) method.

Position-sensitive registration of the dielectric charging process and fiber dynamics was carried out using scanning electron microscope JEOL JSM-T330A at the accelerating voltage of 10 kV. In order to observe the dielectric charging phenomena no metal sputtering has been applied on the sample surface before the SEM studies.

Photo- and video registration of the experiments was performed using a system developed by P. Alexandrov (Shemyakin-Ovchinnikov Institute of Bioorganic Chemistry of the Russian Academy of Sciences) and O. Gradov. Access codes for the full video records of all the experiments in Code-128 standard are given at the bottom of the corresponding tables and figures.

2D Fourier spectra and integral spatial characteristics (ISC) were obtained in real time using QAVIS software based on the FFTW library, developed in V.I. Il'ichev Pacific Okeanological Institute (Far Eastern Branch of the Russian Academy of Sciences).

Charge distribution mapping for “integrated antenna and cable” structures was performed using a discrete differentiation operator, computing an approximation of the gradient of the image intensity function - isotropic 3x3 image gradient operator, or Sobel – Feldman operator (from SAIL - Stanford Artificial Intelligence Laboratory).

Fig. 1. Signal “receiving” and transduction along the polymer fiber.
(Full video recording of this experiment is available at <https://youtu.be/epWhGKAzCtE>).

Results

Initially we studied the ability of a non-sputtered PHB fiber to “receive” an electron beam signal, which was estimated by the fact of dielectric charging of the single fiber surface (see Fig. 1). The possibility of the discrete signal propagation (i.e., charge distribution) over the dielectric surface and the presence of attenuation phenomena were also observed. The contribution of the surface inhomogeneities to maintaining a discrete structure of the charge distribution was also demonstrated.

After evaluating the ability of a non-sputtered microfiber to “receive” an electron beam signal, we studied the micromechanics of its dynamics and response to the changes in the operation modes of the electron microscope (including the electron beam focusing, magnification, accelerating voltage, etc.).

As you can see from the table 1, after increasing the power density, polymer fibers begin to move rapidly under the electron beam and “relax to a metastable state” in a little more than half a minute. Up to this point, a complete reconfiguration of the fiber directions occurs, depending on

their position under the beam, as can be seen from the comparison of 2D Fourier spectra and Integral Spatial Characteristics (ISC) at different times. After that, reversible fiber oscillations also occur, but the whole network topology remains stable, which is consistent with the stability of the ISC symmetry axes, the angular ratios of which vary by only a few degrees.

Table 1.

Time-lapse microphoto	2D Fourier spectrum	ISC
00
08
18
29

Video recording of the experiment is available at <https://youtu.be/uHBLWysbAA>.

In some cases, not smooth movements are observed, leading to a change in the network configuration under the electron beam, but spontaneous instantaneous changes accompanied by a sharp increase or disappearance of ISC components, as shown in Table. 2.

Table 2.

Time-lapse microphoto	2D Fourier spectrum	ISC
00:00:00:900

00:00:07:605

00:00:10:056

00:00:14:859

Video recording of the experiment is available at <https://youtu.be/cl5NegKEng0> .

Table 3.

SEM microphotography	Correlogram (0.4 s.)	Time code
Start
03:590
04:444
05:893

Video recording of the experiment is available at <https://youtu.be/A9tVG6Zu2sl> .

In some cases, a reorganization of the entire structures is observed, which can be applied for the electron-beam-controlled microrobotics. Thus, table 3 includes micrographs and correlograms taken with a temporal resolution of 0.4 seconds for such a reorganized area. It is obvious that exposure to an electron beam induces mechanical changes in the cross-linked micromechanical structure of the polymer. In this case, different fibers work as "jacks", "drive belts", "springs", "elastic beams", "pushers", etc. The mechanical effect observed depends on the irradiated area, that is, the effective cross-sectional area of the scanning electron beam.

It is possible to confirm the assumption that some (thick) fibers perform the functions of bearing elements of mechanical strength, while the others (thin) operate as the flexible elements controlled by the electron beam. Let us consider the experiment with two different structures. In table 4 one can see the movement of a thin flexible fiber (the thread in the upper part of the micrograph) against the stability of the large thick one (in the center). The fiber movement features can be tracked using the data of the wavelet transform (Morlet wavelet) in the Re and Im regions (one can observe the drift of the extremum on the "blue" representation).

The measurements were carried out using the scalographic / scaleographic tool of the QAVIS program (see <http://oias.poi.dvo.ru/qavis/rus/scalogram.html>), which makes it possible to use the appropriate mathematical formalization for their interpretation, excluding the ineffective Gaussian approach.

If some fibers oscillate, move, contract like springs (thin fibers), while others perform a frame function (thick fibers), then the micromechanical properties of the polymer fibers should be assessed in dynamics. It is obvious that a fiber break is a possible cause of damage for the polymer-based controlled microelectromechanical structures, including those for microrobotic or MEMS applications. Therefore, mechanical strength tests should be performed for each chemical or structural type of polymer fibers under the electron beam with different parameters. An example of a PHB fiber break clearly observed on the SEM image is shown in Fig. 2.

Discussion

Where can the above described concept be applied? Obviously, its implementation is possible in different systems operating under vacuum conditions with the priority application area being space technologies. Polymer materials in vacuum are used in dozens of space applications, including vacuum-based 3D printing for in-space satellite assemblies [19]. Possible damages of polymer materials in outer space, including the effect of cosmic rays and elementary particles, are well known and predictable [20-24]. Therefore, the development of polymer robotics for space technologies is not a problem from modern materials science. From the point of view of mechanics, it is necessary to simulate vibrations in a vacuum without taking into account the earth's gravitational force [25], but this is rather a simplification than a complication of the problem.

Table 4.

Video recording of the experiment is available at <https://youtu.be/9M3y3VAt9zY>

Fig. 2. Example of the broken polymer fiber.

Speaking about the application of robotics in space technologies, it is necessary to take into account its long history - from the late 1960s (*sensu lato*, taking into account the automated Babakin spacecrafts in the USSR and a number of similar developments in the USA) or, at least, since the mid-1970s (*sensu stricto*, considering robotic manipulators with automatic decision making function) for interstellar research [26,27]. The main fundamental modern requirements for interstellar robotics are formulated in departmental international meetings of the late 20th - early 21st centuries [28,29]. The difference between the extended interpretation of space robotics and its narrow interpretation is that both mechanically active systems for sensing the external environment and passive mapping systems [30,31] are included in the first, while the narrow interpretation includes only active mechatronic elements such as robotic arms \ manipulators [32].

In our concept, a narrow interpretation prevails, since the dynamics of microfibers, cantilevers under the particle beam makes sense only if there are moving elements - actuators in the spacecraft construction. A similar interpretation is also typical for environment – robot interactions for planetary or terrestrial subsurface explorers / robots based on earthworm locomotion [33,34] and hopping robots for planetary or asteroid surface exploration [35-37]. It should be noted that asteroids do not have an atmosphere and sufficient gravitational force, while planets usually have it. Therefore, in the first case, we can speak about the vacuum systems, which are essentially equivalent to the experimental vacuum conditions in SEM and TEM, and in the second case, only about the similarity with ESEM (Environmental Scanning Electron Microscopy) and ASEM (Atmospheric Scanning Electron Microscopy).

We are not considering here aerial robot explorers for planetary exploration [38], which by definition are not vacuum devices. For the same reason robots with manipulators for exploring planets are beyond the scope of this paper [39-42]. Therefore, in this case, we can only talk about the applications in "open space" and non-atmospheric bodies: meteorites and others [43]. As

practice shows, this indirect and not always accessible way of solving problems (the transition from macroscale to microscale robotics and the introduction of non-standard interpretations despite the inconsistency with the high-budget mainstream) can help in obtaining non-standard results using spacecraft, as was the case decades ago [44-46]. A fibrillar manipulator cannot replace a macromanipulator, but for nanosatellites and picosatellites (such as "CanSat"), sets of cooperative fibrillar manipulators with the electron beam control may be the only possible means of achieving efficiency in many mechanical applications including pulsed one-time manipulations (such as opening a mirror or a solar battery) [47-57].

Launching CanSat into orbit is a separate technical problem, since the suborbital trajectories do not meet the requirements for sufficient evacuation degree and weightlessness. That is, we can speak about the applicability in open space beyond the Karman line (>100 km), and not beyond the Armstrong physiological line of 19 km. However, vacuum studies of potentially applicable polymers have not yet been carried at all the necessary gradations of heights and characteristics of the medium (from atmospheric to vacuum ones). Thus, one can only postulate the presence of a kinematic effect on polymer fibers under the electron beam and speculate about its potential applicability for the purposes of space technology. It should be noted that not all the polymers used in our studies are resistant to the conditions of outer space during long-term exposure. Therefore, this material can be considered only as the first step in this direction, illustrating the physical effect, but not specifying its chemical implementation.

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