Design of Mobile Microrobots with Thermomechanical Actuators

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Abstract: A design concept of a legged mobile microrobot that utilizes thermomechanical actuators is discussed. The forces and torques acting on the legs of the microrobot are identified and analyzed. The phases of motion, conditions of motion, and sequences of operations are defined; the performance characteristics of the robots are studied. A number of design schematics of the microrobot are presented and compared. The issues related to the mechanical structure of the robots, as well as the content and amount of information required by the measurement and control systems are considered. A modified thermomechanical actuator was developed for the microrobot leg. The structure of the actuator involves a feedback sensor. The design sketches of the inspector microrobot with an on-board micromanipulator based on the thermomechanical actuator are proposed. Possible applications of the microrobot for aerospace planet missions are discussed. This study was supported by the Russian Science Foundation (Grant #14-19-00949).

1 INTRODUCTION

Active investigations of moving microstructures based on the thermomechanical principle of operation have been performed for more than 30 years. Various prototypes were developed for effective applications in robotics. Actuators with V-grooves were proposed in (Erdem 2010; Wallace 2006; Zhukov 2012; Norton 2009; Ebefors, 1999; Ebefors, 2000). Most of them are similar to the actuators considered in our study. In papers (Erdem 2010; Popa 2010), the creation of a MEMS hot-wire three-dimensional structure based on a polyimide joint with several V-grooves (Fig. 1) was discussed. The electrical connection of the actuator to the power supply and control units is implemented by means of the metallic buses passing over the V-grooves (Fig. 1, a, b). These buses transmit the control signal to the actuator, which makes it rotate.

Such a structure illustrates the design of sensors for measuring gas flow and moving microrobotic platforms. In addition, scientific results related to the prototype design were obtained in Japan (Ebefors, 1999) in the area of biomorphic structures that use thermomechanical and electrostatic effects, in USA Clark 2012 in the field of microrobots based on thermomechanical actuators, as well as in other countries (God-el-Hak 2002; Harc 2002).

Previous studies dealt with thermomechanical devices involved in the design of the control system for a miniature mirror utilized in aerospace systems (Zhukov, 2014; Wallace, 2006; Zhukov, 2012). Thermomechanical actuators for mobile microrobots intended for space technology were proposed (Zhukov, 2014). In a well-known mobile device “Thermal-powered insect-like robot” (Erdem, 2010), thermomechanical actuators are composed of two polyimide layers with different temperature coefficients of linear expansion. The robot can move in four directions over a plane with a velocity of 3ft/hr. The disadvantage of this device is its impossibility to move over stepped and slope surfaces and a low velocity.

A stepping device “A walking silicon micro-robot” is implemented on a silicon substrate and has two rows of thermomechanical actuators with V-grooves filled up with polyimide (Ebefors, 1999). Among other devices, we can indicate “Microid microrobot” (Clark, 2012) that combines piezoelectric elements and “Microcrawler and conveyor robot” (Popa, 2010) that is installed on a platform with controller and power supply units. Both robots have problems when moving along rough surfaces. Attempts were made to improve characteristics of the termomechanical actuator (Bolotnik, 2015; Gradetsky, 2010; Kozlov 2010;

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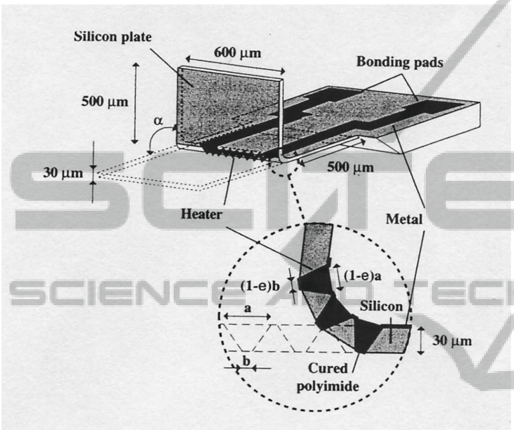
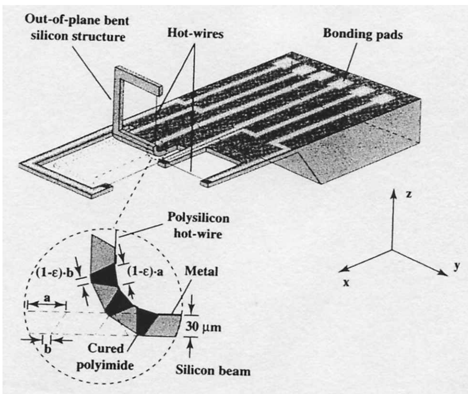
Korpukhin, 2011). Other studies were carried out to develop high-perfomance unimorph actuators based on electrostrictive copolymers (Xu, 2002) and microthermophotovoltaic systems (Yang, 2002). In addition, sensor materials and measurement systems were presented for extreme environments such as high temperature, high pressure, toxicity, nuclear radiation, and electromagnetic pulses (Fahrner, 2001; Kondon, 1997). The question arises on how to design microrobots that possess additional possibilities. In our paper we discuss the following issues:



a)



b)

Figure 1: View of MEMS polyimide joint structure (Ebefors 1999). a) MEMS triple hot-wire; b) Isometric view of a three-dimensioned structure based on polyimide joint with three V-grooves.

- application of a new modified thermomechanical actuator for microrobot design;
- identification of the forces and torques acting on the legs of a mobile microrobot;
- analysis of motion phases and schematics of mobile microrobots.

Solving these problems may help overcome the disadvantages mentioned above and improve the functional parameters of mobile microrobots.

2 MODIFIED THERMOMECHANICAL ACTUATOR FOR MICROROBOT LEG

A modified thermomechanical actuator was developed (Zhukov 2014; Zhukov, 2012; Bolotnik, 2015; Gradetsky, 2010; Kozlov, 2010; Korpukhin, 2011) to improve the functional characteristics of microrobots and enable using them in outer space. A microrobot leg based on this type of actuator contains the following components (Fig. 2):

Polyimide (4) lies mostly in n grooves between neighboring silicon elements 5 (Fig. 2, a, b, c). When an electrical pulse is applied to the silicon elements, the polyimide layer undergoes thermal expansion and the structure bends by an angle ranging from 0 to $n\Delta\alpha$ in the direction to plate 2 to which the actuator is connected; n is the number of grooves in the actuator, $\Delta\alpha$ is the average value of the change in the angle between the faces of the actuator grooves when the actuator deflects from the horizontal position. When cooling, the structure deflects in the opposite direction. Therefore, using polyimide as a material subject to thermal deformation, combined with the silicon heaters connected together by means of a metallization layer, allows providing the motion of the structure. Such actuators can be used, in particular, as the legs of a microrobot.

1 – a thermomechanical actuator, 2 – a base with metallized tracks, 3 – a metallized layer of the sensory element (interdigital structure), 4 – polyimide, 5 – silicon heating elements, 6 – metallization layer heater. In comparison with a familiar design (Fig. 1, a, b), this structure includes functional layer 3 for increasing measurement possibilities (Bolotnik, 2015).

It is supposed that the microrobot based of the actuator under consideration will be used for applications in outer space. This is connected with the stability of the robot components to the conditions of outer space, such as temperature range (-196 °C +400°C), plasma action, low gravity, and no friction influence.

In the proposed device, the active element of the actuator simultaneously plays the role of a sensor, as was shown in (Bolotnik 2015). Therefore, this device can be used simultaneously as an actuator of a mobile robot leg and as a sensor for measuring physical parameters of the robot motion.

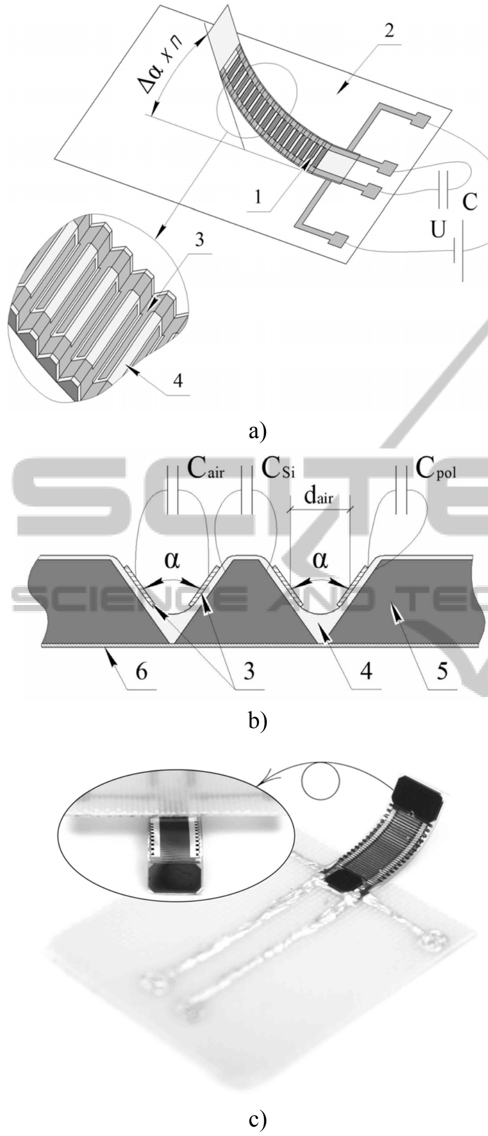


Figure 2: Microactuator combined with a feedback sensor [14]. a) General view of the structure; b) Profile view with V-grooves; c) Experimental prototype of the thermomechanical actuator.

Since the main element of such a microactuator is a cantilever plate, it is necessary to estimate reliability and stability of its mechanical characteristics. It is shown in (Zhukov 2014, Bolotnik 2015) that the angle of thermal deformation of the actuator after fatigue cycle tests involving $5 \cdot 10^6$ cycles decreases by 15% at most, which confirms the possibility of the actuators to be used as robot legs and links of micromanipulators.

3 FORCES AND TORQUES ACTING ON A MOBILE MICROROBOT LEG

In the quasi-static approximation, the forces acting on the leg can be calculated on the basis of the equilibrium equation for a curved beam. The unstrained shape of the beam depends on the temperature and can be changed by heating and cooling the beam. Figure 3 depicts the body of the robot and a supporting leg attached to it. We assume that the leg, modeled by a curved beam, is rigidly clamped to the body at point O. At point O, the clamping force and the clamping torque are acting on the beam. Let the contact of the leg with a supporting surface occur at the end point. At point, two forces are acting on the leg, the adhesive force and the constraint force due to the interaction of the leg with the supporting surface. The adhesive and constraint forces are counterbalanced by the force acting on the leg at point due to deformation of the leg.

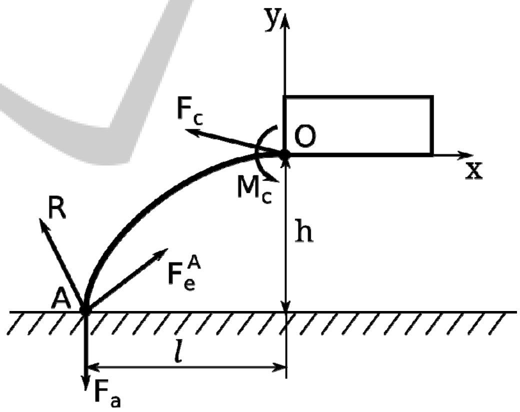


Figure 3: Forces and torques acting on the robot's leg.

The forces and torques featuring in the model under consideration satisfy the equations

$$\mathbf{F}_a + \mathbf{R} - \mathbf{F}_e^A = 0, \quad \mathbf{F}_e^A + \mathbf{F}_c = 0,$$
$$R_x h + M_c = (R_y + F_a) l, \tag{1}$$

where $-l$ and $-h$ are the coordinates of the contact point A in the frame of reference attached to the robot's body as shown in Fig. 3; subscripts x and y indicate the projections of the forces onto the respective axes; the adhesive force is assumed to act along the normal to the supporting surface at point A.

If the positions of points O and A are given, the forces $\mathbf{F}_c$ and $\mathbf{F}_e^A$ and the torque M_c are defined by solving the equilibrium problem for the beam. Then the components of the constraint force **R** are uniquely defined by the equations of balance of forces and torques.

Physically, the components R_x and R_y are the friction force and the normal reaction force, respectively. It is natural to assume that friction between the robot's leg and the supporting surface is dry friction that obeys Coulomb's law. For this case, the quantities R_x and R_y must satisfy the inequality

$$|R_x| \leq \mu |R_y|, \tag{2}$$

where μ is the coefficient of friction. If this inequality does not hold for a prescribed configuration of the system, then the equilibrium of this configuration cannot be ensured physically.

The adhesive force plays an important role for the robots operated in orbital space stations in the state of weightlessness. This force presses the leg to the supporting surface and provides the normal reaction of this surface necessary for creating the force of friction. To provide the adhesive force an adhesive layer should be applied to the contact surface of the leg's foot.

We have considered the simplest model of contact of the leg with the surface, assuming this contact to occur at a single point. More complex and more realistic models, in which the foot is regarded as a plate connected to the beam by a joint, cam also be considered.

4 ANALYSIS OF MODES AND PHASES OF MOBILE MICROROBOT MOTION.

The thermomechanical actuator can be used as a main component of a space microrobot intended for inspection. Experiments show that such an actuator can provide a deflection of the leg by an angle of no less than 30 degrees and develop a force of 0.3 mN. Version one of the design of the mobile minirobot leg (Fig. 4) involves platform (1) and thermomechanical actuators with main (3) and additional (2) zones of deformation. The angle between two actuators is 180 ; the main (3) and additional (2) zones are connected with a polyimid flexible insertion (4). The additional zone (2) forms a pad and is intended for pressing the leg down to the surface and detaching it from the surface. The adhesion layer (5) on the leg enables the robot to move along complex surfaces under various conditions, including a state of weightlessness. Main zone (3) of deformation permits the microrobot to move at least along two planes, in two directions along each of these planes, depending on the operating mode.

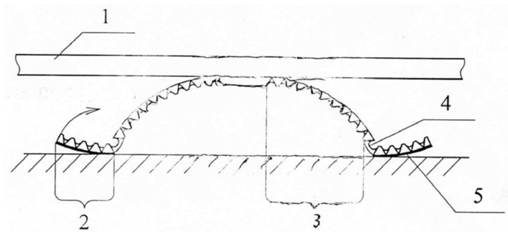


Figure 4: Design of a microrobot leg (version one).

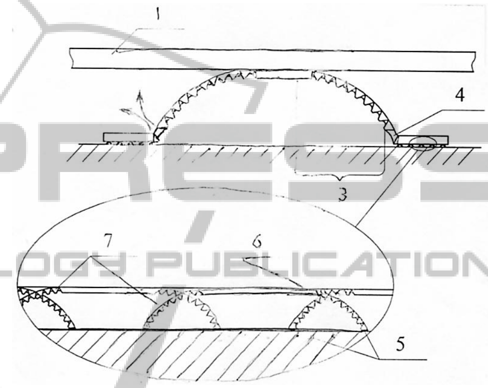


Figure 5: Design of a microrobot leg (version two).

Design version two (Fig. 5) differs from version one in the presence of additional zone (2) that is implemented by a silicon beam with thermomechanical actuators of smaller size. The additional deformation zone serves for the motion of the robot along planar surfaces, while the main zone is used for overcoming uneven stepped segments of the surface.

The experimental prototype of the robotic platform is shown in Fig. 6. This prototype is characterized by the following parameters: voltage up to 20 V, temperature up to 200°C, deviation angle of the actuator up to 60 degrees, the velocity of the platform up to 10mm/min.

The phases of motion for version one of the microrobot design are shown in Fig. 7. Introduce the following notation: t_{lh} is the unbending time for the actuator under heating, t_{lc} the bending time for the actuator under cooling, t_{fh} the unbending time for the pad actuators under heating, t_{fc} the bending time for the pad actuators under cooling (we assume that $t_{fh}<t_{fc}$ and $t_{lh}<t_{lc}$); N_{th} the power supply needed for unbending the leg actuator, N_{fh} the power supply needed for unbending the pad actuator, N_{fs} the power supply needed for keeping the leg in the unbent state, N_{fs} the power supply needed for

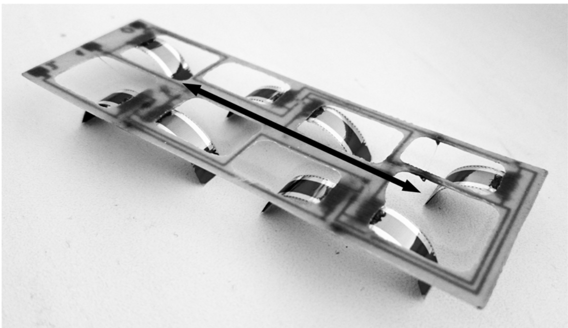


Figure 6: Experimental prototype of the robotic platform.

Figure 7: Motion phases of mobile microrobot.

keeping the pad in the bent state.

Calculate the minimal time required for each phase of motion and the corresponding energy consumption. Let the legs and the pads be bent in the initial position. Below, we characterize each (*i*th) phase and give the expressions for the duration t_i of this phase and the respective energy consumption A_i

1. Unbending four legs and two front pads:

$t_1=t_{lh}$, $A_1=4N_{lh}\ t_l+2N_{fh}\ t_{fh}$

2. Bending two front legs and unbending two rear pads; two rear legs and two front pads being kept unbent:

$t_2=t_{lc}$, $A_2 = 2N_{fh}\ t_{fh}+2N_{ls}\ t_{lc}+2N_{fs}t_{lc}+2N_{fs}\ (t_{lc}-t_{fh})$

3. Bending two rear legs, all pads being kept unbent: $t_3=t_{lc}$; $A_3=4N_{fs}\ t_{lc}$

4. Bending two front pads, the rear pads being kept unbent:

$t_4=t_{fc}$, $A_4=2N_{fs}t_{fh}$

5. Unbending two front legs, the rear legs being kept bent:

$t_5=t_{lh}$, $A_5=2N_{lh}\ t_{lh} + 2N_{fs}\ t_{lh}$

6. Unbending two rear legs, all pads and the front legs being kept unbent:

$t_6=t_{lh}$, $A_6=2N_{lh}\ t_{lh}+4N_{fs}\ t_{lh}+2N_{ls}\ t_{lh}$

7. Bending two rear pads, two front pads and all legs being kept unbent: $t_7=t_{fc}$, $A_7=2N_{fs}\ t_{fc}+4N_{ls}\ t_{fc}$

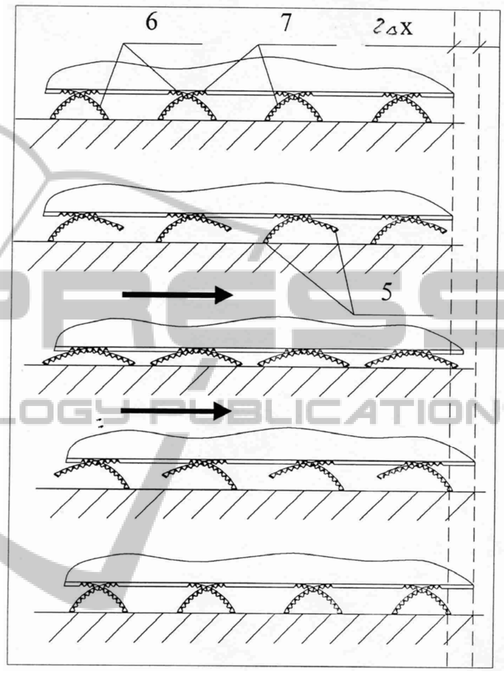


Figure 8: Mode of motion of the mobile microrobot along a flat surface.

Phases 2-7 are then repeated. Phase 1 starts the motion of the robot from the initial state. Time t_1 and energy A_1 are needed for this phase.

Time $t_\omega=t_1+t_2+t_3+t_4+t_5+t_6+t_7$ and energy $A_\omega=A_2+A_3+A_4+A_5+A_6+A_7$ are needed for one cycle of the motion along a straight line:

$$\begin{aligned} A_\omega &= 2N_{fh}t_{fh} + N_{ls}\left(2t_{lc}+2t_{lh}+4t_{fc}\right) \\ &+N_{fc}\left(8t_{lc}-2t_{fh}+6t_{lh}+4t_{fc}\right)+4N_{lh}t_{lh} \end{aligned} \tag{3}$$

The experiments with a prototype of the actuator demonstrate the following time and power characteristics: t_{lh}=4s, t_{lc}=9s, t_{fh}=2s, t_{fc}=5s, N_{lh}=1,36W, N_{ls}=0,45W, N_{fh}=0,68 W, N_{fs}=0,23 W

Then the energy and time needed for one cycle of motion along a straight line on a horizontal plane are given by $A_\omega = 70.94$ J, $t_\omega = 36$ s.

The phases of motion of an inspector microrobot (version two) along flat and stepped surfaces are shown in Fig. 8 and Fig. 9, respectively.

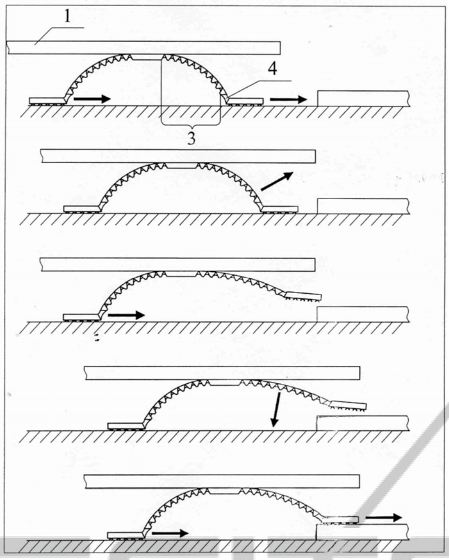


Figure 9: Mode of motion of the mobile microrobot along a stepped surface.

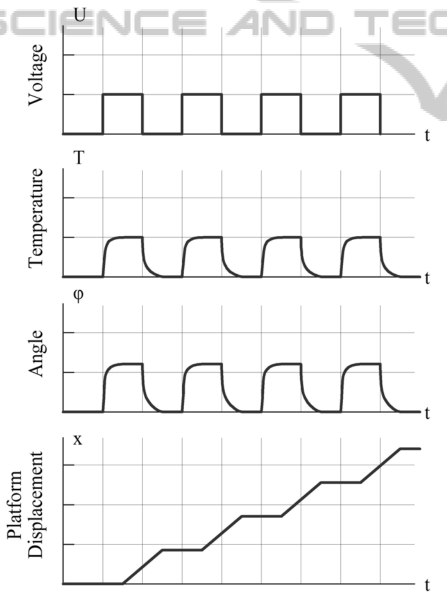


Figure 10: Motion cyclogram of the microrobot leg.

The microrobot leg motion cyclograms (Fig. 10) plots the time histories of the control voltage, temperature of the actuator, the angle of deflection of the leg, and the displacement of the robot. The control voltage heats the actuator plate, which causes its deflection by an angle of up to 90°.

The general view sketch of the inspector microrobot is depicted in Fig. 11. The microrobot has a micromanipulator based on thermomechanical actuators. This robot can be used for space exploration purposes. For example, it can grasp ground samples of planets and put them into a container (Fig. 12).

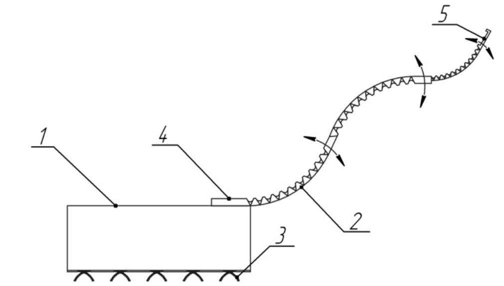


Figure 11: The general view sketch for an inspector microrobot.

5 CONCLUSIONS

Major problems related to designing microrobots on the basis of new type of thermomechanical actuators are discussed. Mechanical structures of the robots,

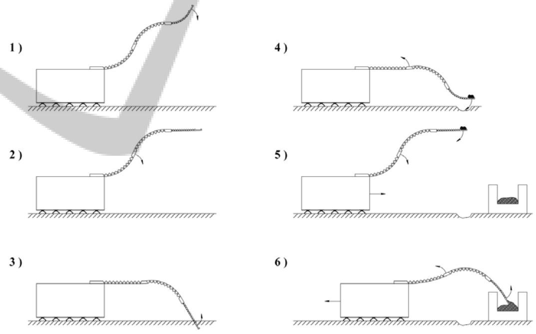


Figure 12: Inspector microrobot taking ground samples.

acting forces, phases and conditions of motion are considered and analyzed. A concept of an inspector microrobot for planet missions is proposed. A mathematical model of the motion of the robot is developed to study and simulate the behaviour of robot subject to various external conditions. Parametric analysis will of the model and experimental studies of the prototype of such a robot are planned.

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