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AN APPROACH TO COMPLIANT LOCOMOTION SYSTEMS BASED ON TENSEGRITY STRUCTURES

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ABSTRACT

Tensegrity structures are prestressed compliant structures composed of a set of disconnected rigid compressed elements connected by continuous prestressed tensional elements. A spatially limited, local impact on tensegrity structures yields a global change of their shape. This essential property initiates the development of novel compliant locomotion systems with large shape variability and simple system design. The development of locomotion systems based on tensegrity structures has just begun. In the contribution three locomotion systems based on tensegrity structures are presented. In contrast to the known approaches the considered systems differ in their actuation / locomotion schemes. The working principle of the introduced locomotion systems is discussed and verified with experimental tests.

Index Terms - tensegrity, locomotion, mechanical compliance, prestressed compliant structures

1. INTRODUCTION

Terrestrial locomotion systems are dominated by systems with legs and wheels, but they have a limited field of application and are difficult to miniaturise [1]. Future microrobots with high mobility require the use of non-conventional locomotion and actuation principles. In many applications, such as the inspection of complex environments or biomedical applications, an intrinsic mechanical compliance of these systems and their large shape variability are advantageous [2]–[5].

Several methods are known, to realize locomotion systems with large shape variability. Shape changing robots are primarily based on systems, using of a large number of interconnected elementary robot modules, which can change their relative position. The moving of the robot modules causes that the robots can change their shape and location [6], [7]. The disadvantage of the most known systems is their lack of mechanical compliance. In addition to this method, the development of the first shape changing locomotion systems as compliant single locomotor units has recently begun [8]–[10].

Globally prestressed compliant structures enable large shape variability with a small number of actuators. Tensegrity structures represent one particular type of these structures.

Tensegrity structures are prestressed mechanical structures, consisting of a set of rigid compressed elements (struts) connected by continuous tensional members (strings) (Figure 1). The aim of a wide shape variation and mechanical compliance can simply be realized using these structures if the tensional members have a pronounced elasticity. A spatially limited, local impact on the tensegrity structure yields a global change of their shape, independent from the relative position of the actuator. This enables their ability for locomotion on irregular or rough terrain. Furthermore, the foldability of tensegrity structures is an important property, which is especially useful for transport in aerospace applications.

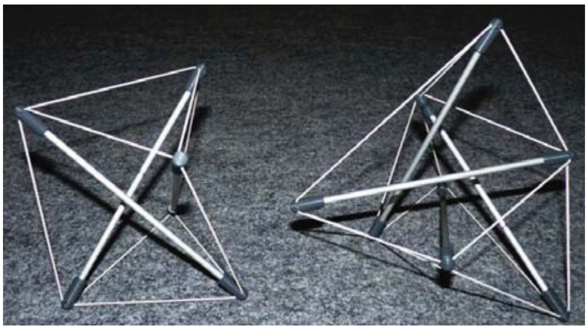

Fig. 1. Three-strut (left) and four-strut (right) tensegrity structure (thick elements – struts, thin elements – strings)

The development of locomotion systems based on tensegrity structures has just begun. To the authors, five published prototypes are known: (1-2) the three prism tensegrity structure, also called “Simplex” (composed of 3 struts + 9 strings), (3) the four prism tensegrity structure (4 struts + 12 strings) which realize walking locomotion [11]–[13], and (4-5) two crawling locomotion systems based on the icosahedron shape (6 struts + 24 strings) [14] and on a semiregular polyhedral body (12 struts) [15]. These systems are assigned to tensegrity structures of class 1 – the struts are not directly connected. The first three prototypes are characterized by a small number of elements together with comparatively moderate shape variability. The manifold shape variability of the fourth and fifth prototype is realized by a large number of elements and actuators.

In general, three possibilities are available to realize locomotion systems based on tensegrity [16]:

- elementary tensegrity system
- collocated system, composed of several units, whereat each unit is able to move separately and independent from the other ones and is based on tensegrity
- collocated system, composed of several units, whereat each unit is able to move separately and independent from the other ones but is not based on tensegrity

In the following we describe three systems which belong to the first group. The aim is to realize tensegrity locomotion systems, which are less fault-prone, have a simple and functional structure driven by as less as possible actuators. With respect to systems of the second group, whose aim is addressed to a modularised system design, geometric shapes with as much as possible symmetry planes will be investigated. The first aim is to design and to realize a locomotion system based on tensegrity which allows manifold shape variability in spite of less elements used (Prototype A). Furthermore, two prototypes are introduced, based on 3D tensegrity structures with a minimum number of struts. Prototype B, based on curved struts, is in contrast to the known solutions capable to perform a pure rolling locomotion. Prototype C is a vibration driven locomotion system.

2. GEOMETRIC CONFIGURATION OF THE PROTOTYPES

2.1. Prototype A

A simple spatial tensegrity system defines a cubic structure [17] whereat the twelve edges consist of strings (Figure 2, thin black lines) with spring stiffness c_1, initial length b_1 (strings according to type 1). The trigonal vertices are connected by four rigid struts (i=0,1,2,3) of the same length L (Figure 2, thick black lines). Due to the aspired manifold shape variability, the six face diagonals of the cube are connected by six additional strings (Figure 2, thin gray lines) defined by spring stiffness c_2, initial length b_2, such that an equilateral tetrahedron is generated within the cube (strings according to type 2). Therefore, one end of each strut (j=0) is connected with six strings (three strings of type 1 and 2, respectively) and the other end (j=1) with three strings of type 2.

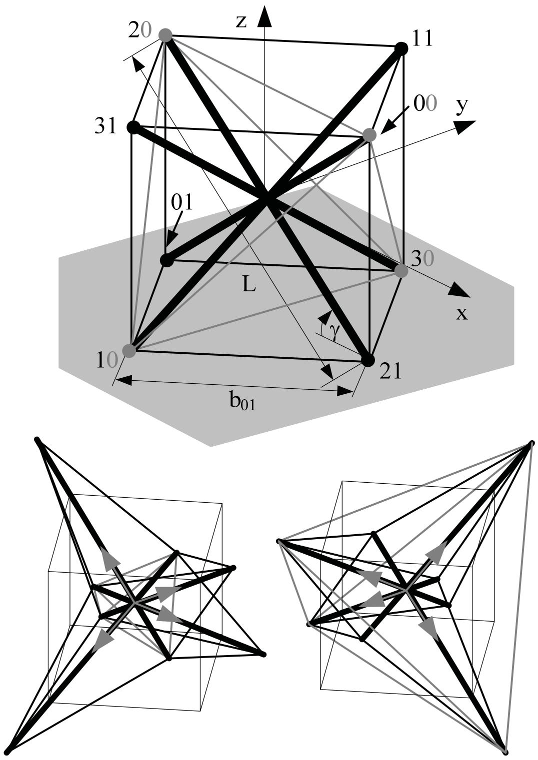

Fig. 2. Top: schema of the tensegrity structure for the prototype A, thick black lines – struts, thin black lines – strings of type 1, gray lines – strings of type 2, bottom: two selected configurations for different values of c_1, c_2, b_1 und b_2, gray arrows – shift of the struts compared to the initial configuration

In the special case characterized by $c_2 \rightarrow 0$ and $b_1 < b_{01}$, the structure always has a cubic shape independent from c_1 neglecting the structure's own weight. In cases, different from this one, an equal shift (displacement) V_i=const. of the centre of gravity (CG) of the struts along the appropriate axial direction compared to the total CG is obtained. Because of the symmetry these shifts V_i (depending on c_1, c_2, b_1 and b_2) are equal to each other (Figure 2 bottom). Therein the structure has a convex or non-convex symmetric shape whereat the shape can be characterized by the parameter V. In this symmetric case, the angles between the struts are independent from the spring stiffnesses c_1 and c_2 and from the original lengths b_1 and b_2 and are equal to the angles which also exist in the cubic shape. In this case the coordinates for the vertices can be described in dependence of V (V>0 if the vertices with six strings are displaced in direction to the total CG of the structure):

$$P_{ij} = a \cdot \cos(j \cdot \pi) \cdot \begin{pmatrix} \cos(\gamma)\cos(i \cdot \pi/2) \\ \cos(\gamma)\sin(i \cdot \pi/2) \\ \sin(\gamma)\cos(i \cdot \pi) \end{pmatrix}; \; i = 0,1,2,3; \; j = 0,1$$

with $a = L \cdot \left(\frac{1}{2} + \frac{V}{L} \cdot (2j-1) \right)$ and $\gamma = \sin^{-1}\left(1/\sqrt{3}\right)$.

In order to determine the shape of the structure in dependence of both string types, the spring forces dependent on V have to be determined. This expression is obtained by means of the spring force law and geometric considerations:

$$\left|\vec{F}_1\right| = c_1 \cdot L \cdot \left(\sqrt{1+\left((2V/L)^2-1\right)\cdot\cos^2\gamma} - b_1/L\right)$$
$$\left|\vec{F}_2\right| = c_2 \cdot L \cdot \left(\left(1-2V/L\right)\cdot\cos\gamma - b_2/L\right)$$

Considering the equilibrium and focusing on the struts finally yields the relation between c_1, c_2, b_1, b_2 and V:

$$1-\frac{2V}{L}-\frac{b_2/L}{\cos\gamma}=\frac{c_1}{c_2}\cdot\frac{4V}{L}\cdot\left(\frac{b_1/L}{\sqrt{1+\left((2V/L)^2-1\right)\cdot\cos^2\gamma}}-1\right)$$

Figure 3 shows the displacement V depending on b_1 and b_2 in case of $c_1=c_2$. The gray area indicates that both string types are stressed by tensile forces within the initial configuration. The same figure shows that in case of compressive stressed strings of type 1, which deviates from the tensegrity principle but nevertheless is possible, several equilibrium positions of the structure are available.

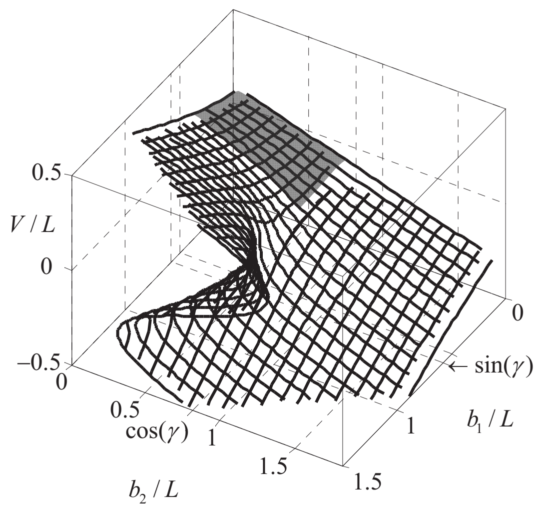

Fig. 3. Displacement V in dependence of b_1 and b_2 for $c_1=c_2$, gray area – both string types in initially tension stressed configuration

The application of different strings ($c_k\neq$const., $b_k\neq$const., k=1,2) within one group of string types causes an undesirably reduction of the structure's symmetric planes and is therefore not considered.

2.2. Prototypes B and C

The tensegrity structure, based on [18], for the prototype B consists of two equal curved struts with constant radius of curvature R and length $R\pi$ (Figure 4). The struts are indirectly interconnected through eight springs. Each endpoint of the struts is connected with the both endpoints of the other strut (four strings of tpye 1 between 00-10, 00-11, 01-10 and 01-11, initial length b_1, spring constant c_1). Furthermore, the strut points 02 at $\varphi_0=\pi/2$ and 12 at $\varphi_1=\pi/2$ are connected with the end points of the other strut (4 strings of tpye 2 between 02-10, 02-11, 12-00 and 12-01, initial length b_2, spring constant c_2).

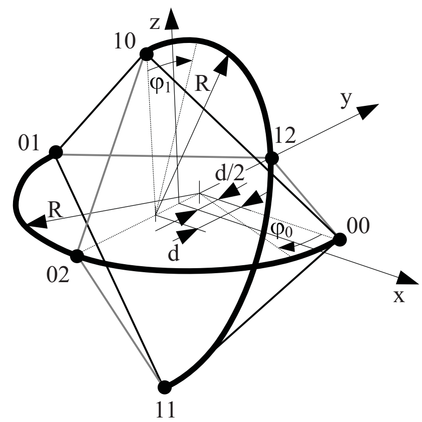

Fig. 4. Top: schema of the tensegrity structure for the prototypes B and C, thick black lines – struts, thin black lines – strings of type 1, gray lines – strings of type 2

The shape of the structure can be expressed only by the parameters d (distance between the arc centre points) and R. Considering the equilibrium, the coordinates of the spring attachment points to the struts and the parameter d are given by the expression:

$$P_{ij}=R\cdot\begin{pmatrix}(1-i)\cdot(1-j/2)\cdot(1-3j)\\ (i-1/2)\cdot\left(j\cdot(j-1)-d^*\right)\\ i\cdot(1-j/2)\cdot(1-3j)\end{pmatrix};\ i=0,1;\ j=0,1,2$$

with

$$\frac{d^*}{1-d^*}=\frac{c_2}{c_1}\cdot\frac{1-\dfrac{b_2^*}{\sqrt{2+(d^*)^2-2d^*}}}{1-\dfrac{b_1^*}{\sqrt{2+(d^*)^2}}};\ d^*=\frac{d}{R};\ b_1^*=\frac{b_1}{R};\ b_2^*=\frac{b_2}{R}$$

The geometric configuration of prototype C is a modified version of the above introduced structure, excluding the strings of type 1 and the curved struts replaced with angled struts (bending angle: $\pi/2$).

3. PROTOTYPES – EXPERIMENTAL EVALUATION

3.1. Prototype A

A simple possibility of locomotion of the first considered tensegrity structure is the periodic, phased and axial displacement of the struts along their longitudinal axis by means of linear actuators.

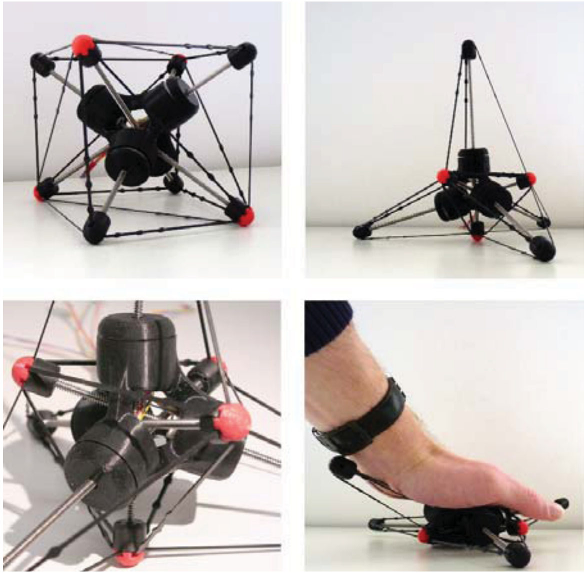

Fig. 5. Prototype A, top left – cubic shape, top right – selected symmetric shape, bottom left – enlarged view: stepping motors and string-strut connections, bottom right – compressed state

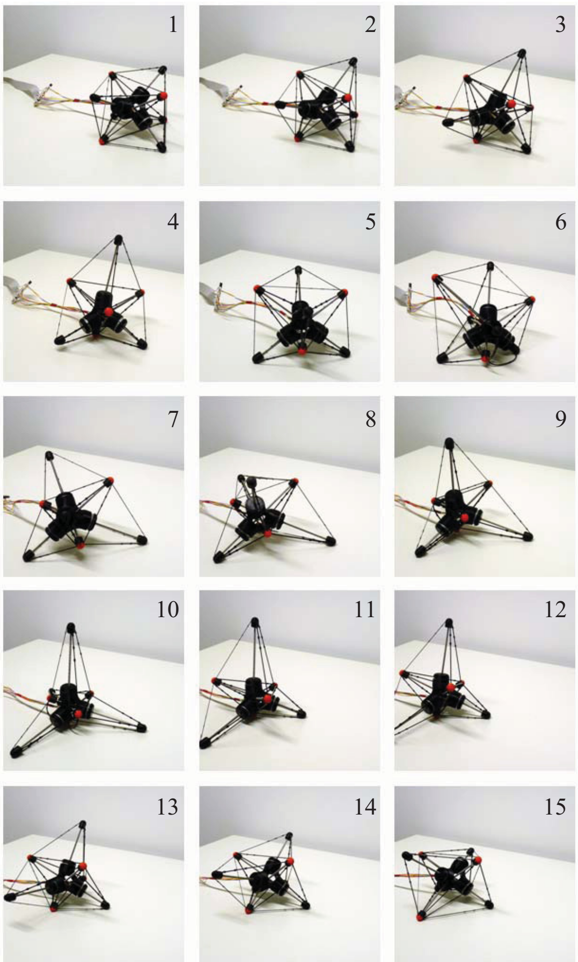

Fig. 6. Prototype A, Locomotion sequence (1→15)

In the prototype the struts are formed by jackscrews (Figure 5) [19]. Their displacements induce stepping motors which are arranged in the centre of the system and are connected to each other by compliant joints. Therefore, this system can be regarded as tensegrity system of class 2 – the struts are connected directly with each other. The strings are represented by elastomer filaments with the initial length b_1=b_2=60 mm and a cross sectional area of 2 mm^2. The space diagonal of the system equals L=160 mm. The linear actuators allow a movement range of the struts of round about 100 mm with a maximum velocity of 20 mm/s. The prototype has a total mass of 220 g. The locomotion of the system is verified by experimental tests (Figure 6). Within the plotted sequence all four struts are displaced phased to enable the locomotion.

3.2. Prototype B

The application of curved struts in tensegrity structures indicates their potential ability for rolling locomotion. The second locomotion system (Figure 7, total mass: 168 g, radius of curvature of the struts R=80 mm, d^*=0.6), on the basis of the in Ch. 2.2 introduced structure, is capable for uniaxial rolling and also for movement in plane with combined tip over and rolling (Figure 8) [20]. The movement of the system is induced by internal mass displacement. Two equal internal masses (m_m=34 g) can be moved along the lines connecting the end points of the curved struts with two linear stepping motors.

For the tip over movement, the following requirement must be fulfilled:

$$l^*_{max} > 2 \cdot (2 - d^*) \cdot (1 - d^*)$$

with l^*_{max} - maximal movement range of each internal mass (normalized to the radius of curvature R of the strut).

Fig. 7. Prototype B, top – isometric views, bottom left – side view, bottom right – compressed state

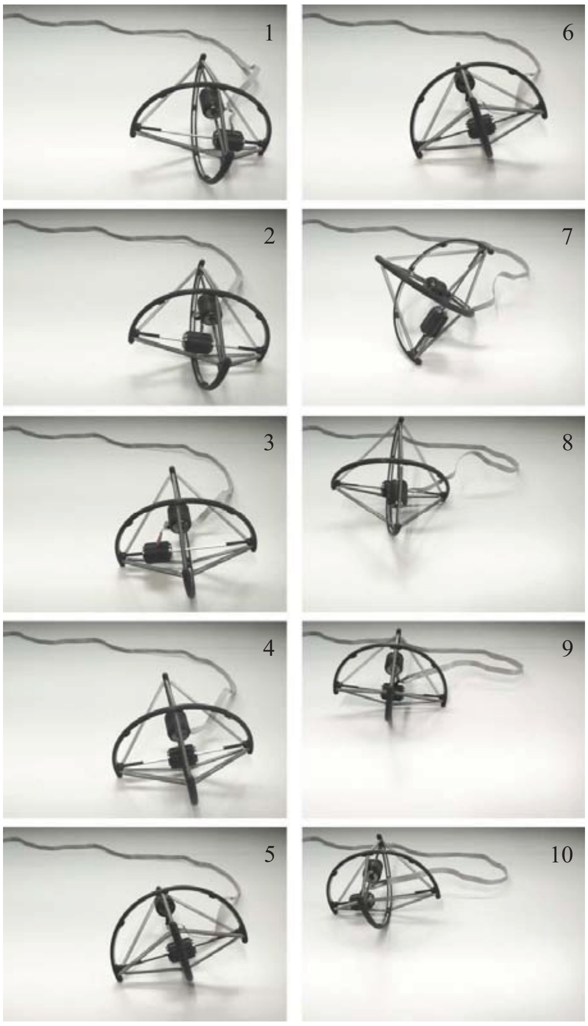

Fig. 8. Prototype B, locomotion sequence (1→10), movement types: 1-3, 9-10: tip over, 4-8: rolling

3.3. Prototype C

The third locomotion system (Figure 9, total mass: 31 g, space diagonal: 130 mm), on the basis of the in Ch. 2.2 introduced structure, is capable for uniaxial bidirectional locomotion [20]. The movement of the system is vibration induced by direct force transmission between the struts, caused by equal dynamic excitation of two electromagnets, which are located at the inflexion points of the angled struts (Figure 10).

Due to the possible different modes of vibration of the system, the prototype is able to perform uniaxial locomotion in two opposite directions. The direction of the movement can be defined with the excitation parameters (driving frequency, current amplitude, duty-cycle).

With an asymmetrical arrangement of electromagnets it is conceivable to realize locomotion in the plane. The replacement of an electromagnet with a permanent magnet in this case allows the realization of planar vibration driven locomotion systems, based on tensegrity structures, which are powered with only a single actuator.

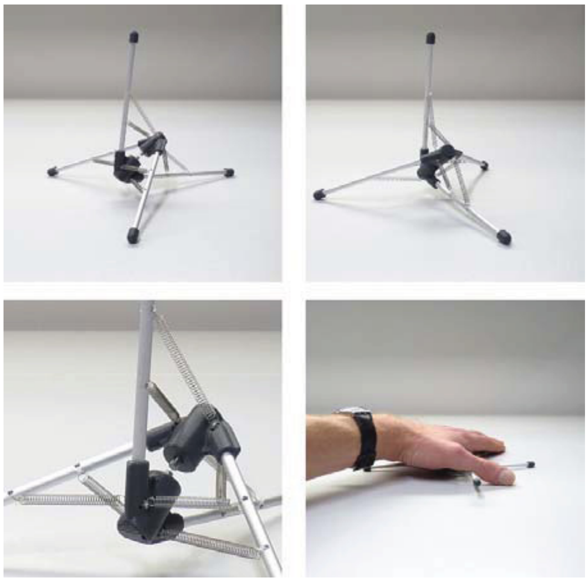

Fig. 9. Prototype C, top – isometric views, bottom left – enlarged view: electromagnets and string-strut connections, bottom right – compressed state

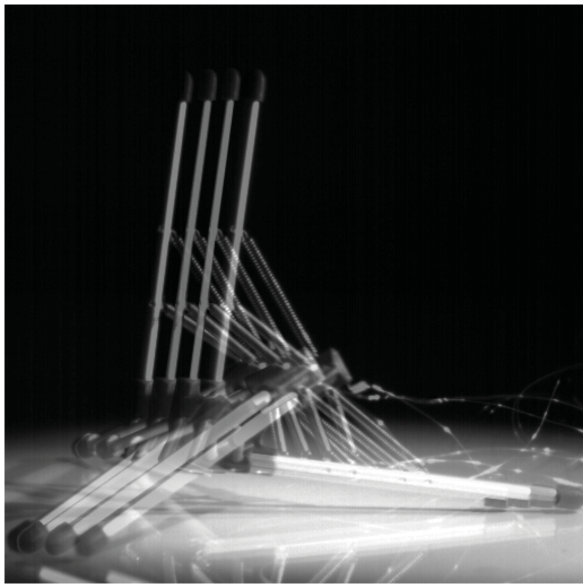

Fig. 10. Prototype C, locomotion sequence, excitation: periodic square wave signal with 50% duty cycle, driving frequency: 25 Hz, 4 Periods

4. CONCLUSION

This paper presents new concepts for locomotion systems based on tensegrity structures. Selected basic design principles for locomotion systems based on tensegrity were discussed focusing on possible actuating schemes and simple geometric configurations.

As a first example, a tensegrity structure with a simple and functional shape and manifold shape variability was discussed. The system performance was verified by experimental investigations by means of a prototype of the tensegrity class 2 (Prototype A). The system was driven by the displacement of struts.

Prototype B is a 3D class 1 tensegrity structure, based on two curved struts. The prototype demonstrates, that rolling locomotion is possible with tensegrity structures. The movement of the system is induced by internal mass displacements.

The locomotion system - prototype C is based also on a 3D class 1 tensegrity structure with minimal number of struts. In contrast to the known solutions, the shape change is realized through direct force transmission between the struts. The locomotion is vibration induced. A complex mode of vibration of this prestressed compliant structure can be induced by dynamic electromagnetic excitation. By proper design, the mode of vibration can be varied in a wide range in dependence of the driving frequency. The use of this effect allows the realization of locomotion systems based on tensegrity structures with simple design and frequency controlled variable movement performance.

5. ACKNOWLEDGMENTS

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