Social humanoid robot SARA: development of the wrist mechanism

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Abstract. This paper presents the development of a wrist mechanism for humanoid robots. The research was conducted within the project which develops social humanoid robot Sara – a mobile anthropomorphic platform for researching the social behaviour of robots. There are two basic ways for the realization of humanoid wrist. The first one is based on biologically inspired structures that have variable stiffness, and the second one on low backlash mechanisms that have high stiffness. Our solution is low backlash differential mechanism that requires small actuators. Based on the kinematic-dynamic requirements, a dynamic model of the robot wrist is formed. A dynamic simulation for several hand positions was performed and the driving torques of the wrist mechanism were determined. The realized wrist has 2 DOFs and enables movements in the direction of flexion/extension 115°, ulnar/radial deviation ±45° and the combination of these two movements. It consists of a differential mechanism with three spur bevel gears, two of which are driving and identical, while the last one is the driven gear to which the robot hand is attached. Power transmission and motion from the actuator to the input links of the differential mechanism is realized with two parallel placed identical gear mechanisms. The wrist mechanism has high carrying capacity and reliability, high efficiency, a compact design and low backlash that provides high positioning accuracy and repeatability of movements, which is essential for motion control.

1. Introduction

In the near future, humanoid robots will be working in direct contact with humans, in an environment that is dynamic and unstructured, and will be performing numerous and complex tasks. One of expectations of modern society is the use of humanoids as an acceptable aid for people with special needs, regardless of whether they have a disability or have impaired mobility and motoric functions due to their old age. This kind of robots must be safe both for humans and for objects in their environment. Apart from this, humanoid joints – mechanisms of which are formed, must fulfil numerous requirements that exist during dynamic activity of the robot. Those are high carrying capacity and reliability, high efficiency, low noise, low vibration, low backlash which is essential for motion control, self-locking that provide the robot posture without actuator power supply, compact design etc. Therefore, special attention should be given to the design and realization of the wrist.

This paper presents the development of a wrist mechanism for humanoid robots. The research was conducted as part of the project which develops social humanoid robot Sara that should represent a mobile anthropomorphic platform for researching the social behavior of robots – Figure 1. The robot will be able to communicate verbally and nonverbally. For expressing facial expressions, biologically
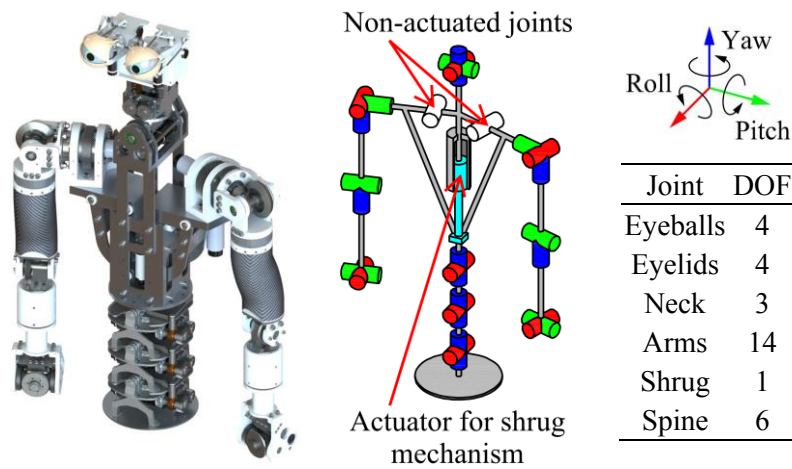
Figure 1. Social humanoid robot SARA: current prototype and its kinematic structure

inspired eyes are being developed with eyelids and eyelashes with total 8 DOFs [1], [2]. To extend the spectrum of nonverbal communication, the robot will be able to shrug if a question is confusing or it does not know what to answer [3-6]. In addition, Sara will have two anthropomorphic arms with 14 DOFs, a self-locking neck mechanism with 3 DOFs [7] and a self-locking multi-segment lumbar spine with 7 DOFs [8] to increase the mobility of the upper body without moving the lower body.

The paper is structured as follows: the first section shows the research motivation; the second section presents the analysis of existing solutions of the humanoid wrists; within the third section, a new wrist solution is proposed – dynamic analysis of the wrist was performed and proposed solution of wrist mechanism is presented in detail; the fourth section summarizes the paper contribution and outlooks future work.

1.1. Human wrist and its mobility

The wrist is a complex structure that connects the hand to the forearm. It allows the hand and fingers to function, it provides and controls the extension and contraction of the long flexors and extensors of fingers and it enables fine hand motoric. It consists of the radiocarpal joint that enables extension of the wrist, the mediocarpal joint for flexion movements of the wrist, the intercarpal joint consisting of a number of smaller joints and the radioulnar joint that enables forearm rotation. Large number of muscles and ligaments is involved in wrist movements. The wrist movements are extension – bending backward (Figure 2a), flexion – bending forward (Figure 2b), radial deviation – moving the palm to the left (Figure 2c) and ulnar deviation – moving the palm to the right (Figure 2d). The range of flexion movements is 80÷90°, while the range of extension movements is 70÷75°. Wrist movement in the direction of radial/ulnar deviation is approximately 60°, which is 15÷25° for movements of radial deviation, respectively 35÷45° for movements of ulnar deviation [9], [10].

<center>(a)   (b)   (c)   (d)</center>
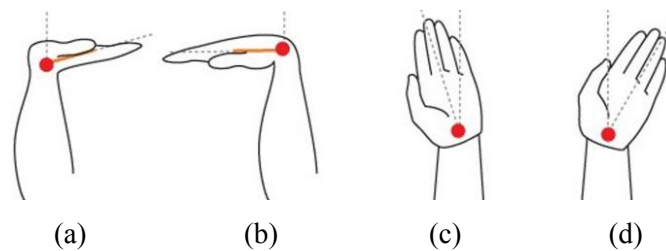
Figure 2. The movements of human wrist: (a) bending backward – extension, (b) bending forward – flexion, (c) palm motion to the left – radial deviation and (d) palm motion to the right – ulnar deviation

2. State of the art

There are two basic groups of robots capable to move the hand independently of the forearm by activating the wrist. The first group of robots has a wrist with 1, 2 or 3 by which each joint has 1 DOF – rigid structures, while the second group of robots has a wrist with 1 joint (condylar joint with 2 DOFs or ball-and-socket joint with 3 DOFs) – flexible structures.

   Wrist with 1 DOF – movements about the yaw or pitch axis, are found in Affetto [11], Ever-1 [12], EveR-2 [13], CB^2 [14], ASIMO [15], HRP-4C [16] etc., wrist with 2 DOFs – movements about the yaw and pitch axes, are found in iCub [17], Robonaut 2 [18], Albert HUBO [19], AILA [20], TORO [21], KIBO [22], HUBO [23], WABIAN-2 [24], KOBIAN [25], ARMAR-III [26], SURALP [27] etc., while the wrist with 3 DOFs – movements about the yaw, roll and pitch axes, are found in James [28], Justin [29], Romeo [30], BERT2 [31], WE-4RII [32], HRP-4 [33] etc. The wrist mechanism of these robots usually consists of rigid and low backlash mechanisms that are interconnected – harmonic drive, cable-driven mechanism, spatial linkage mechanism, spindle drive, low backlash gears etc. In addition to having high carrying capacity and reliability, the advantage of these mechanisms is low backlash that provides high positioning accuracy that enables high accuracy and repeatability of movements, which is essential for motion control.

   Biologically inspired wrist structures with 1 joint and 2-3 DOFs – movements about the yaw and pitch axes or yaw, roll and pitch axes, are found in Kenta [34], Kenji [35], Kotaro [36], Kojiro [37], Kenzoh [38], Kenshiro [39] and Kengoro [40]. The wrist of these robots consists of human-like bones and artificial muscles that are based on nonlinear spring units – NST, which has a nonlinear ratio between the tension and the spring constant of the tendon. Therefore wrist has variable stiffness which is possible to mechanically adjust. The advantage of NST is the simple realization and implementation by using only one spring and guided pulleys of tendon – wire.

3. Wrist mechanism

The primary requirement for the realization is adequate hand mobility about the roll and pitch axes. The wrist supposed to provide the position and orientation of the hand, because the hand must be in the appropriate position relative to the object with which intends to manipulate. Hand is position on the certain location by the arm, while the wrist provides the orientation. Therefore wrist must have more DOFs. Figure 3 shows a possible wrist design based on a differential mechanism. It consists of two driving gears G_1 and G_2, meshed with driven gear G_3 to which the hand of the robot is attached.
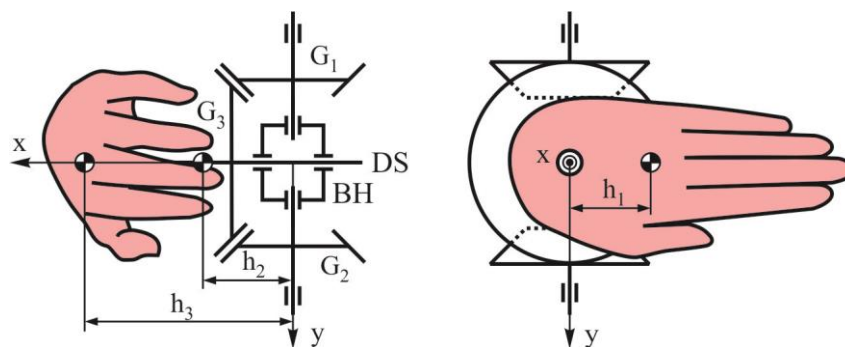

Figure 3. Kinematic scheme of the differential mechanism: G_1 and G_2 – driving bevel gears, G_3 – driven bevel gear to witch the robot hand is attached, DS – driven shaft and BH – bearing housing

3.1. Forces and torques

The hand of the robot is still in development wherefore is approximated with a 1 kg object whose centre of mass is located at distance h_1 relative to the wrist. Movements of the hand supposed to be as natural as possible and therefore is adopted that their duration is no longer than 1 s, which has certain dynamic effects as consequences. Based on the preliminary 3D model of the robot arm, a dynamic model of the wrist is formed and dynamic simulation is performed within which the driving torques of

the wrist mechanism are determined. Three characteristic cases were examined, depending on the type of hand movements and the range of motion. The first one is in the direction of flexion/extension and the range of motion –90° to 15°, the total of 115° – Figure 3a, the second one is in the direction of ulnar/radial deviation and the range of motion –45° to 45°, the total of 90° – Figure 3b, and the third case includes simultaneous movements in the direction of flexion/extension –90° to 0° and ulnar/radial deviation –45° to 0° – Figure 3c. It should be noted that the forearm is immovable and that the hand is appropriately positioned.
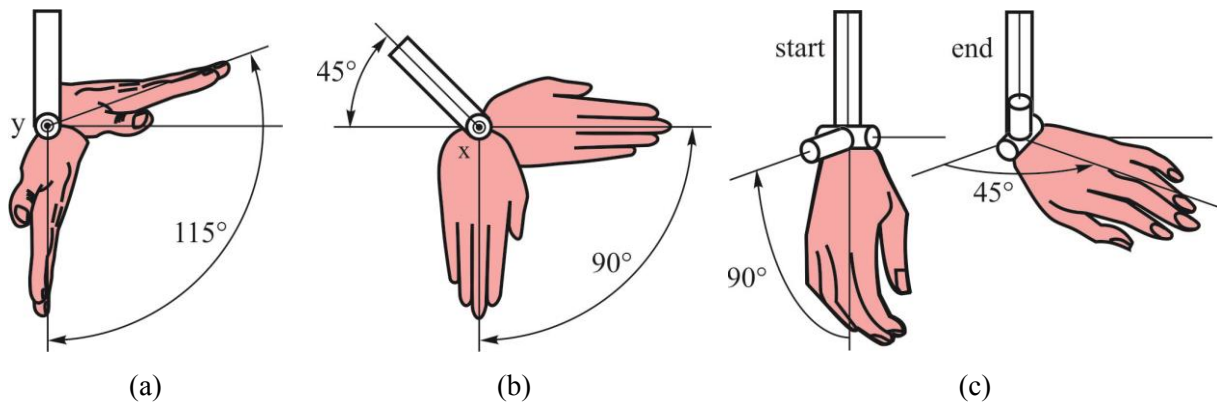
Figure 4. Dynamic simulation of the wrist mechanism: (a) flexion/extension of the hand from –90° to 15° – forearm is immovable and in vertical position, (b) ulnar/radial deviation of the hand from –45° to 45° – forearm is immovable and rotated by 45°, (c) simultaneous flexion/extension from –90° to 0° and ulnar/radial deviation from –45° do 0° – forearm is immovable and in vertical position

The adopted laws of motion of angle φ, angular velocity ω and angular acceleration ε are:

$$\varphi = H\left(\frac{t}{T}\right)^3\left[10 - 15\left(\frac{t}{T}\right) + 6\left(\frac{t}{T}\right)^2\right] \tag{1}$$

$$\omega = \left(\frac{30H}{T}\right)\left(\frac{t}{T}\right)^2\left[1 - 2\left(\frac{t}{T}\right) + \left(\frac{t}{T}\right)^2\right] \tag{2}$$

$$\varepsilon = \left(\frac{60H}{T^2}\right)\left(\frac{t}{T}\right)\left[1 - 3\left(\frac{t}{T}\right) + 2\left(\frac{t}{T}\right)^2\right] \tag{3}$$

where: T – duration of the movement and H – amplitude of the movement (maximum angle). The driving torques of the wrist about the x and y axes are defined as:

$$M_x = \left(m_H g \cos\varphi_y h_1 \sin\varphi_x\right) + \varepsilon_x\left(J_{Hx} + J_{Gx}\right) \tag{4}$$

$$M_y = \left(m_H g \sin\varphi_y h_1 \cos\varphi_x + m_H g \cos\varphi_y h_2 + m_G g \cos\varphi_y h_3\right) + \varepsilon_y\left(J_{Hy} + J_{Gy}\right) \tag{5}$$

where: m_H – mass of the hand, g – gravitational acceleration, m_G – mass of shaft DS with gear G$_3$, J_{Hx}, J_{Hy} – moments of inertia of the hand about x and y axes, J_{Gx}, J_{Gy} – moments of inertia of the shaft DS with gear G$_3$ about x and y axes, φ_x, φ_y – rotation angles about x and y axes, $\varepsilon_x, \varepsilon_y$ – angular acceleration about x and y axes, h_1, h_2, h_3 – centres of mass coordinates of individual segments, seen Figure 3. Table 1 shows the values of the input parameters – segment masses, centres of mass and the appropriate moments of inertia.

Table 1. Input parameters

| m_H	m_G	J_{Hx}	J_{Hy}	J_{Gx}	J_{Gy}	h_1	h_2	h_3
[kg]	[kg]	10^{-4}[kgm^2]	10^{-4}[kgm^2]	10^{-7}[kgm^2]	10^{-4}[kgm^2]	[m]	[m]	[m]
1	0.1	117	122	335	346	0.1	0.012	0.02

Given the Eqs. (1) – (5), dynamic simulation of the wrist mechanism has been performed and driving torques were determined – Figure 5. Based on the dynamic analysis, the maximum value of the driving torque for dimensioning of the wrist mechanism is 0.93 Nm.

(a)   (b)   (c)
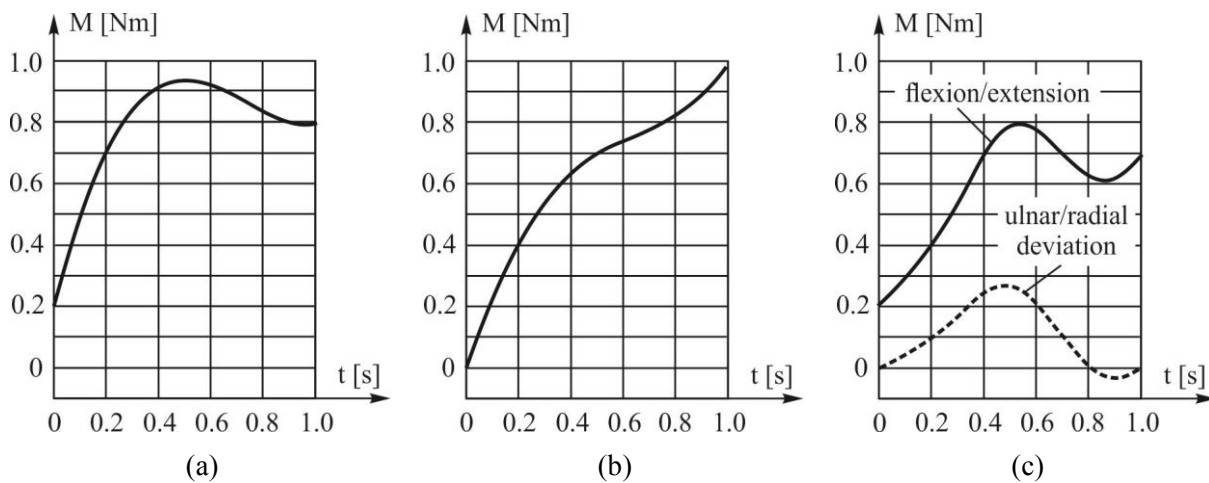
Figure 5. Time histories of the driving torque: (a) movement of flexion/extension (b) movement of ulnar/radial deviation and (c) simultaneous movement of flexion/extension and ulnar/radial deviation

3.2. Mechanical design
The realized wrist has 2 DOFs and enables hand movements in the direction of flexion/extension 115°, ulnar/radial deviation ±45° and the combination of these two movements – Figure 6. It consists of a differential mechanism with three spur bevel gears, two of which are driving and identical, while the last one is the driven gear. If driving gears have the same circumferential velocity and the same direction of rotation, hand moves about the pitch axis – flexion/extension movements, and for the opposite direction of rotation, hand moves about the roll axis – ulnar/radial deviation. If the circumferential velocities of driving gears are different, a combination of these two movements is obtained.


(a)   (b)
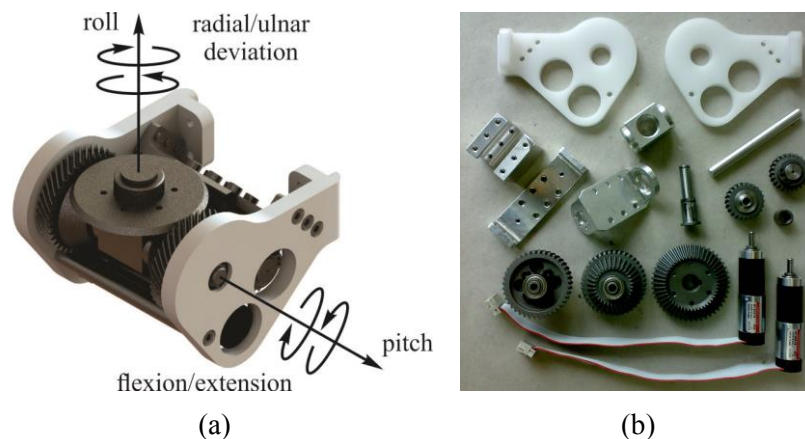
Figure 6. Wrist mechanism: (a) CAD model and (b) constitutive parts

Structure of the wrist mechanism is presented in Figure 7. It consists of three subassemblies, two of which are driving and identical, while the third one is driven to which robot hand is attached. Driving subassembly consists of an actuator and elements for power transmission and motion – driving shafts, helical gears, driving bevel gear, bearings etc. Actuator consists of a DC motor with graphite brushes, planetary gearhead with 3 stages and a magnetic encoder. Driving helical gear is directly attached to the gearhead shaft, while driving bevel gear is fixed to the driven helical gear that represent driving shaft. Driving subassembly consists of driven shaft, bearings, bearing housing and an output link of differential mechanism – driving bevel gear to which robot hand is attached. Low backlash in helical and bevel gear pairs is achieved by precise machining of gears, support structures and preloading – center distance is done with negative tolerance. Realized wrist mechanism is shown in Figure 8 and its configuration is given in Table 2. Hight of the wrist mechanism is 70 mm, its width is 80 mm, its length is 85 mm, while mass is 0.57 kg.
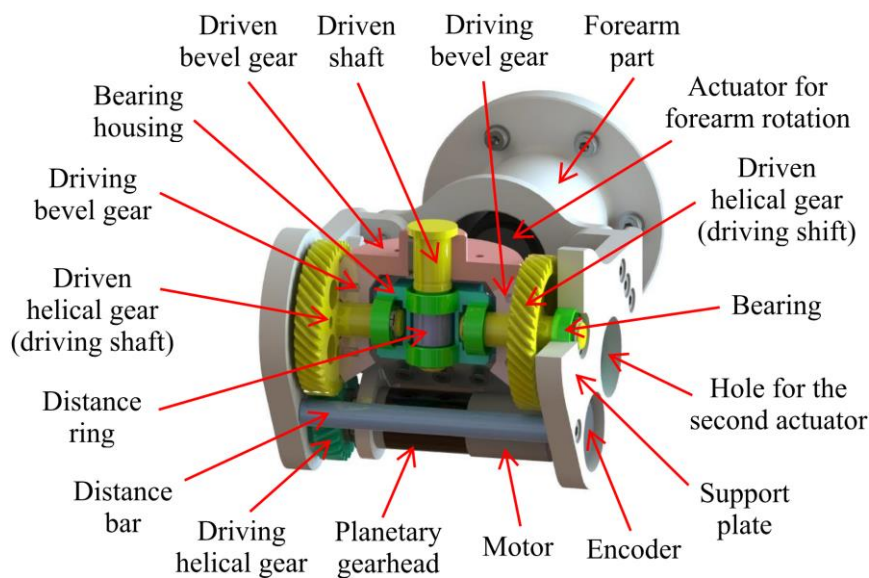
Figure 7. Wrist mechanism with details – cross section
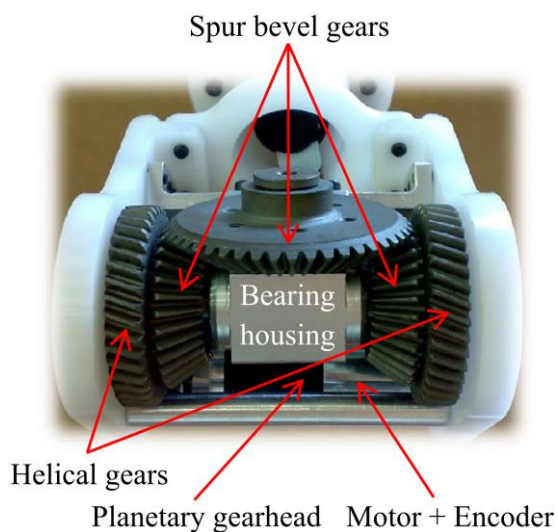
Figure 8. Wrist mechanism of the robot Sara

Table 2. Wrist mechanism configuration

Maxon motor RE-max 17 (2 pcs.)	Voltage [V]	24
	Power [W]	4
	Torque [mNm]	3.63
	Speed [rpm]	8520
Planetary gearhead GP 16-C (2 pcs.)	Reduction	157
	Torque [Nm]	0.4
	Efficiency [%]	73
Encoder MR-ML (2 pcs.)	Channels	3
	Counts per turn	512
Gearing with helical gears (2 pcs.)	Reduction	1.74
	Module [mm]	0.9
	Helix angle [°]	20
Gearing with bevel gears (2 driving & 1 driven)	Reduction	1.5
	Module [mm]	1
	Helix angle [°]	0

4. Conclusion

This paper presents the development of a wrist mechanism for humanoid robots. Considering that the hand is position on the certain location by the arm, while the wrist provides the orientation, basic requirement for the wrist realization is adequate mobility about pitch and roll axes. Having in mind the analysis of humanoid wrists, we proposed new wrist that require small actuators. Based on the kinematic-dynamic requirements, a dynamic model of the robot wrist is formed. A dynamic simulation for several hand positions was performed and the driving torques for the wrist mechanism were determined. The realized wrist has 2 DOFs and enables movements in the direction of flexion/ extension 115°, ulnar/radial deviation ±45° and the combination of these two movements. It consists of a differential mechanism with three spur bevel gears, two of which are driving and identical, while the third one is the driven gear to which the robot hand is attached. If driving gears have the same circumferential velocity and the same direction of rotation, then the movements about the pitch axis – flexion/extension of the hand are obtained, and for the opposite direction of rotation, movements about the roll axis – ulnar/radial deviation of the hand are obtained. If the circumferential velocities of driving gears are different, a combination of these two movements is obtained. Power transmission and motion from the actuators to the input links of the differential mechanism is realized with two identical helical gear pairs. Wrist mechanism has high carrying capacity and reliability, high efficiency, compact design and low backlash that provides high positioning accuracy that enables high accuracy and repeatability of movements, which is essential for motion control. Further work will be focused to the minimization of the overall dimensions as well as to the reduction of the backlash by using spiral bevel gears with small modules.

Acknowledgments

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