A Hybrid Soft Actuator Inspired by Grass-Spike: Design Approach, Dynamic Model, and Applications

Dong-Woon Choi 1,2, Cho-Won Lee 2, Duk-Yeon Lee 2, Dong-Wook Lee 2, and Han-Ul Yoon 3,*†

1 Department of Mechanical Convergence Engineering, Hanyang University, Seoul 04763, Korea; acelluce@hanyang.ac.kr
2 Applied Robot R&D Department, Korea Institute of Industrial Technology, Ansan 15588, Korea; chowon2932@kitech.re.kr (C.-W.L.); proldy@kitech.re.kr (D.-Y.L.); dwlee@kitech.re.kr (D.-W.L.)
3 Division of Computer and Telecommunication Engineering, Yonsei University, Wonju 26493, Korea
* Correspondence: huyoon@yonsei.ac.kr; Tel.: +82-33-760-2235
† Current address: 1 Yonseidae-gil, Wonju, Gangwon-do 26493, Korea.

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Abstract: This paper presents the bio-mimetic design approach, the dynamic model, and potential applications for a hybrid soft actuator. The proposed hybrid soft actuator consists of two main parts: a cylinder-shaped rigid core and soft silicone spikes wrapped around the core’s surface. The key idea of the proposed design approach is to mimic the movement of a grass-spike at a functional level by converting the vibration force generated by a small electric motor with a counterweight in the rigid core into a propulsion force produced by the elastic restoration of the spikes. One advantage of this design approach is that the hybrid soft actuator does not need to be tethered by a tube line from an air compressor and is more amenable to fine control. In addition, the hybrid soft actuator can be modularized with a wire and a tubular passage, which in turn work as a linear actuator. The dynamic model of the hybrid soft actuator can be derived by applying Lagrangian mechanics, and unknown system parameters can be identified by the optimization process based on the empirical data. Two applications—an elbow manipulator and a robotic hand grasper—demonstrate the feasibility of the proposed actuator to perform a muscle-tendon action successfully.

Keywords: soft robotics; bio-mimetic design; hybrid soft actuator; hybrid soft actuator module; elbow manipulation; robotic grasping

1. Introduction

Soft robotics is a novel approach to the design of entire robotic systems or partial mechanisms by imitating the structural characteristics or functional mechanisms of various living creatures. Autumn et al. observed that a gecko can stay on a vertical, dry, flat, slippery surface and found that the adhesive force between the gecko’s toes and the surface is proportional to the shearing force. Based on this, they invented Stickybot [1]. Inspired by the underwater movement and grasping technique of octopuses, Cianchetti et al. invented the OCTOPUS robot [2]. Hawkes et al. demonstrated a biological vine-like manipulator actuated by air pressure through a thin pipe, which was originally inspired by the growth mechanism of fungi or grapevines [3]. Shin et al. invented Hygrobot, which imitates the behavior of a seed in the presence of humidity [4]. All these approaches have shown that soft robotics can provide us with new perspectives to address challenging issues in the field of robotic system design.

An important issue for traditional electro-magnetic actuators is that their mass and volume are typically proportional to the generated torque; accordingly, the safety issues should be considered,
for example in a workplace where human workers and robots coexist. To ensure safety, the boundary of the robot’s workspace needs to be known, which in turn makes it difficult to adapt the workplace to a new arrangement or to deploy the requisite facilities when a production process changes [5]. To solve this issue, one way is to employ a machine learning algorithm to predict the human workers’ movement and prevent a collision with the robotic systems [6]; another way is to design a robotic system whose mass is reduced, resulting in a small moment of inertia, which eventually helps to prevent exceeding the safety limits [7].

In soft robotics, robotic systems are made of soft materials, e.g., silicone or textile, which guarantee enough flexibility and dexterity to mimic the behavior of a living organism [7–10]. The tetrapod robot developed by Harvard University is able to adapt its walking pattern with respect to the environmental situation such as the shape of the terrain, various obstacles, etc. [11]. The GoQBot from Tufts University was inspired by caterpillars’ ballistic rolling mechanism by which it can replicate a fast self-propelled rotary locomotion [12]. Cao et al. at Bristol University showed a reconfigurable crawling robot that uses dielectric elastomer actuators to convert the change in the electro-magnetic field into a propulsion force to move forward [10]. One common feature of the aforementioned soft robots is using air pressure as a source of actuation; accordingly, the robots are tethered to an air supply tube, which might impose a limitation on the robot’s workspace.

Vibration-driven locomotion might have the potential to make soft robots free from being tethered by a power line, as well as from being actuated by air pressure. Zhan et al. proposed a miniature vibration-driven planar locomotion robot for which the velocity could be controlled by two solenoids [13]. Bristle-bots have also been popular in the field of small robotic system design (either soft or rigid) due to vibration-driven characteristic and compactness. Cicconofri et al. presented a bristle-bot that was made of a polymer material for the body and two paper legs and its modeling [14]. Studies from various perspectives have been reported; for instance, the group behavior of multiple bristle-bots [15], the design of a millimeter-scale bristle robot (body length less than 10 mm) [16], and so on.

Since soft robots have “soft” bodies, the modeling approaches for rigid body mechanisms cannot be applied directly, and the modeling process of soft robots is known to be difficult by its nature. Marchese, Tedrake, and Rus introduced an approach to address this problematic issue for their elephant trunk-like manipulator [17]. They first regarded the elephant trunk-like manipulator as a continuum of multiple segments. Then, they applied the Euler–Lagrange equation as a tool to derive a dynamic model. Consequently, the dynamic model of the elephant trunk-like manipulator could be obtained, which was similar to a typical rigid body model structure [17,18]. Becker developed a bristle-bot, described the kinetic energy and potential energy explicitly, and presented the movement of his robotic system including anisotropic friction based on the principle of virtual work. He also proposed an approach in which the Euler–Lagrange equation served as a primary tool to obtain the equation of motion [19,20]. Therefore, by following the above-mentioned approaches, we can obtain the dynamic model of soft robotic systems.

In this paper, we propose a hybrid soft actuator inspired by a grass-spike. If we place the grass-spike on a taut wire and apply vibration to the rope, the elasticity of the spikes is converted into a propulsion force; consequently, it moves. The moving direction depends on the leaning angle of the spikes. To mimic the movement characteristic of the grass-spike at a functional level, the proposed hybrid soft actuator consists of a rigid core part, as well as a soft spike part wrapped around the rigid core. The rigid core part is a cylinder-shaped body, and it has a small motor with a counterweight to generate vibration inside the body. The soft spike part has aligned silicone spikes on a flat silicone substrate. The term “hybrid soft” comes from this structural feature, designed to have a rigid core + soft spikes, and the proposed actuator will be referred to as a “hybrid soft actuator (HSA)” throughout the paper. If we attach a wire to the end of the HSA and place it in the tubular passage, then it can drag/manipulate a mass attached to the other end of the wire. Being modularized with a wire and a
tubular passage, the HSA is able to work as a linear actuator. This modularized HSA will be referred to as a hybrid soft actuator module (HSAM).

In addition to our design approach, we also introduce two dynamic models: an HSA model and an interactive control model between the HSAM and a mass, respectively. By following the approaches introduced in [18,19], we first derive the HSA model. We also introduce a system identification process to estimate unknown frictional parameters based on empirical data. The interactive control model can be derived by analyzing the HSAM and the mass as a bilateral control system. Again, the system identification process is followed to estimate the damping effect. The simulation results are presented for both models; in particular, the outcomes from the HSAM simulation will be used to determine the number of HSAMs to generate a desired amount of force. Lastly, two potential applications—an elbow manipulator and a robotic hand grasper—are presented to demonstrate the feasibility of the HSA and HSAM to be utilized for soft robotics applications. The rest of the paper is organized as follows: Our HSA design approach is presented in Section 2. The derivation of the dynamic model of the HSA and the interactive control model of the HSAM is introduced in Section 3. Section 4 discusses the experiments to validate the derived model and estimate the unknown friction and damping parameters by the system identification. The simulation results for the HSA and the HSAM are depicted in Section 5. Section 6 gives the conclusion of this paper.

2. Hybrid Soft Actuator Design

2.1. Appearance Inspired by a Grass-Spike

Figure 1 shows the appearance and subpart assemblies of the proposed HSA. From the inside to the outside, the HSA mainly consists of three subparts: (i) a cylinder-shaped rigid core equipped with a vibration motor (a small motor with a counterweight) and a moving direction switch, (ii) soft silicone spikes, and (iii) an outer case that changes the leaning angle of the silicone spikes, as well as serves as a housing for all the subparts. The silicone spike was made with a metal silicone mold and liquid silicone (PM5000, hardness 39, Yeungnam traders). The spikes were aligned on a patch-type thin silicone substrate and wrapped around the rigid core. When the rigid core vibrates, the elasticity of the spikes converts this vibration into a propulsion force; accordingly, the HSA moves toward the direction set by the leaning angle of the spikes. Indeed, both generating the vibration and changing the moving direction can be done by a single motor by adopting our custom-made part denoted as the “switch”, as shown in Figure 1. The details will be introduced below.

Figure 1. The appearance and part assemblies of the proposed HSA. The switch is a sort of all-in-one mechanism that allows the HSA to generate vibration and change the moving direction by a single motor.
2.2. All-in-One Mechanism to Move and Change Direction

Figure 2 illustrates the aforementioned “switch” mechanism to enable the HSA to move toward a desired direction by a single motor. The switch mechanism consists of a custom-made gear and a pin attached to the outer case (see Figure 1). When the motor rotates, the vibration is generated by the counterweight, and the pin moves along the spiral guide of the switch and will eventually be positioned either in the leftmost or rightmost slot with respect to the rotating direction. Accordingly, the outer case (attached to the pin) pushes the spikes to change the leaning angle of the spikes, which in turn determines the moving direction of the HSA. Namely, the HSA can be actuated toward one direction just by rotating the motor either clockwise or counter-clockwise. By adopting the above-mentioned design approach and all-in-one switch mechanism, the HSA can mimic the movement characteristics of a grass-spike at a functional level.

![Figure 2. The switch mechanism that enables the HSA to generate vibration and change the leaning direction by a single motor: The pin will be positioned either in the leftmost or rightmost slot of the switch with respect to the rotating direction of the motor, which in turn determines the leaning direction of the spikes. Blue arrows indicate the HSA’s moving direction according to the pin positions.](image)

3. Dynamic Models

3.1. A Single HSA Model

Figure 3 depicts the free body diagram of the proposed HSA. To obtain a dynamic model, we start by recapitulating the modeling approach introduced in [21]. Since the obtained model will be utilized for a system identification process to estimate an unknown friction parameter, we substitute the signum function in [21] with a hyperbolic tangent function to lessen the effect of discontinuity during an optimization process. Table 1 summarizes the variables and parameters appearing in the free body diagram shown in Figure 3.

![Figure 3. The free body diagram of a hybrid soft actuator.](image)
Table 1. The definition of the variables and parameters appearing in Figure 3. rev, revolution.

| NAME                      | SYMBOL | VALUE       | UNIT    |
|---------------------------|--------|-------------|---------|
| Total mass                | $m_0$  | 34          | g       |
| Horizontal mass           | $m_1$  | 10.5        | g       |
| Vertical mass             | $m_2$  | 10.5        | g       |
| Spike length              | $l$    | 8           | mm      |
| Initial spike angle       | $\phi_0$ | $\frac{\pi}{6}$ | rad     |
| Number of spikes          | $n$    | 140 EA      |         |
| Stiffness constant of spikes | $c$   | $8.7 \times 10^{-4}$ Nm/rad |
| Coefficient of friction   | $\mu = \mu_+ = \mu_-$ | Needs to be identified |
| Sampling time             | $\Delta t$ | 0.0001 s |         |
| Motor revolution speed    | $\Omega$ | input variable | rev/s  |
| HSA displacement          | $x$    | state variable | mm      |
| Spike leaning angle       | $\phi$ | state variable | rad     |

Suppose that the HSA moves along the $x$-axis. The total kinetic energy $K$ is equal to the sum of three kinetic energies corresponding to the HSA movement, vibration $\xi$ with respect to the $x$-axis, and vibration $\eta$ with respect to the $y$-axis; therefore:

$$K = \frac{m_0}{2}(\dot{x}^2 + \dot{y}^2) + \frac{m_1}{2}(\dot{x} + \dot{\xi})^2 + \frac{m_2}{2}(\dot{y} + \dot{\eta})^2. \quad (1)$$

The total potential energy $P$ is equal to the sum of the potential energies corresponding to the three material points, represented by $m_0, m_1, m_2$, and the elasticity of the spikes; thus:

$$P = (m_0 + m_1)gy + m_2g(y + \eta) + n\frac{c}{2}(\phi - \phi_0)^2. \quad (2)$$

From Figure 3, the position and velocity of $O'$ with respect to the $y$-axis, denoted by $y$ and $\dot{y}$, can be represented as:

$$y = l \cos \phi + a \quad (3)$$
$$\dot{y} = -\phi l \sin \phi \quad (4)$$

where $a$ is the radius of the HSA. Substituting Equations (3) and (4) into Equations (1) and (2) yields:

$$K = \frac{1}{2}(m_0 + m_1)x^2 + \frac{1}{2}(m_0 + m_2)\dot{\phi}^2 + m_1\dot{x}\dot{\xi} - m_2l\phi\eta \sin \phi + \frac{m_1}{2}\dot{\xi}^2 + \frac{m_2}{2}\dot{\eta}^2 \quad (5)$$
$$P = (m_0 + m_1)gy + m_2g(y + \eta) + n\frac{c}{2}(\phi - \phi_0)^2. \quad (6)$$

To apply the Euler–Lagrange equation of (where $\mathcal{L} = K - P$):

$$\frac{d}{dt} \left( \frac{\partial \mathcal{L}}{\partial \dot{q}_i} \right) - \frac{\partial \mathcal{L}}{\partial q_i} = Q_i, \quad \text{where} \quad q_i = x \text{ or } \phi, \quad (7)$$

an external force $Q_i$ should be defined. By the principle of virtual work, if a point $x_i$ (where the ground and the $i$th spike contacts) is moved by $F_i$ as $\delta x_i$, then the sum of $F_i\delta x_i$ must be equal to the work done by the external force $Q_i$. Thus, we have:

$$Q_x \delta x + Q_\phi \delta \phi = F_1 \delta x_1 + F_2 \delta x_2 + \cdots + F_n \delta x_n := \delta W \quad (8)$$
From the geometric relationship, we can easily obtain the following:

$$x = x_1 + l \sin \phi + d \quad \Rightarrow \quad x_1 = x - l \sin \phi - d$$

(9)

Accordingly,

$$x_i = x_1 + b \cdot i = (x - l \sin \phi - d) + b \cdot i \quad \Rightarrow \quad \delta x_i = \delta x - l(\cos \phi)\delta \phi$$

(10)

where \(d\) is the distance from the center of mass of the HSA \(x\) to the root of the first spike and \(b\) is the gap between the spikes. Substituting Equation (10) into Equation (8) yields:

$$\begin{align*}
\delta W &= Q_2 \delta x + Q_\phi \delta \phi \\
&= F_1 \delta x_1 + F_2 \delta x_2 + \cdots + F_n \delta x_n \\
&= F_1 (\delta x - l(\cos \phi)\delta \phi) + F_2 (\delta x - l(\cos \phi)\delta \phi) + \cdots + F_n (\delta x - l(\cos \phi)\delta \phi)
\end{align*}$$

(11)

Since the external force only depends on \(x\) and \(\phi\), we have:

$$\begin{align*}
Q_x &= \frac{\partial (\delta W)}{\partial (\delta x)} = F_1 + F_2 + \cdots + F_n \\
Q_\phi &= \frac{\partial (\delta W)}{\partial (\delta \phi)} = -l(F_1 + F_2 + \cdots + F_n) \cos \phi
\end{align*}$$

Substituting Equations (5), (6), (12), and (13) into Equation (7) yields:

$$\begin{align*}
(m_0 + m_1)x + m_1 \ddot{x} &= F_1 + F_2 + \cdots + F_n, \quad \text{for } q_i = x \\
(m_0 + m_2)^2 \ddot{x} \sin \phi - (m_0 + m_2)^2 \ddot{\phi} \sin \phi \cos \phi + nc_2(\phi - \phi_0) - m_2 \ddot{\phi} \sin \phi - (m_0 + m_1 + m_2) g \ddot{x} \\
&= -l(F_1 + F_2 + \cdots + F_n) \cos \phi, \quad \text{for } q_i = \phi
\end{align*}$$

(14)

(15)

The friction force \(F_i\) can be calculated as:

$$F_i = -\mu N_i \tanh(\dot{x} - l \dot{\phi} \cos \phi)$$

(16)

where \(N_i\) and \(\mu\) are the normal force and the friction coefficient, respectively. From Figure 3, \(N_i\) can be obtained by considering the motion of the center of mass of the HSA; thus:

$$(m_0 + m_2) \ddot{y} = N_1 + N_2 + \cdots + N_n - (m_0 + m_2) g$$

(17)

and \(\ddot{y}\) can be easily calculated from Equation (4). We finally have:

$$N_1 + N_2 + \cdots + N_n = (m_0 + m_2)(g - \ddot{\phi} \sin \phi - \ddot{\phi} \cos \phi) + m_2 \ddot{\phi}$$

(18)

The friction coefficient \(\mu\) is anisotropic; therefore, it can vary as follows:

$$\mu = \begin{cases} 
\mu_+, & \text{if } \dot{x} - \ddot{\phi} \cos \phi < 0 \\
\mu_-, & \text{if } \dot{x} - \ddot{\phi} \cos \phi > 0
\end{cases}$$

(19)

In Table 1, most of the parameters can be determined by practical measurement; however, the friction coefficient will be identified later on by the system identification process based on the empirical data. The details of the system identification process will be discussed in Section 4.2.

Finally, by substituting Equations (18) and (19) into Equations (14) and (15) and rearranging for state variable \([\phi, \dot{\phi}, x, \dot{x}] = [\phi, \omega, x, v]\), we obtain the equation of motion for the HSA. For the numerical simulation, we can express it as a discrete time version with a sampling time \(\Delta t\); consequently,
\[
\begin{align*}
\phi_{k+1} & = \phi_k + \Delta t \cdot \omega_k \\
\omega_{k+1} & = \left( \omega + \Delta t \left( (m_0 + m_2)l^2 \cos \phi_k \sin \phi_k - \mu \cos \phi_k \tan \left( \nu_k - l \omega_k \cos \phi_k \right) \right) \right) \omega_k^2 \\
& - g \left( (m_0 + m_1 + m_2) \sin \phi_k - \mu (m_0 + m_2) \cos \phi_k \tan \left( \nu_k - l \omega_k \cos \phi_k \right) \right) \\
& + nc (\phi_k - \phi_0) + m_2 l \cos \phi_k \tan \left( \nu_k - l \omega_k \cos \phi_k \right) \left( \phi_k - \phi_0 \right) \right) / \left( -(m_0 + m_2) \right) \\
x_{k+1} & = x_k + \Delta t \cdot v_k \\
v_{k+1} & = \left( \nu_k + \Delta t \left( m_1 \nu + \mu \left( (m_0 + m_2) \right) \left( g - l \omega_{k+1} \right) \cos \phi_k - l \cos \phi_k \omega_k^2 \right) \right) \\
& + m_2 \nu k \cdot \tan \left( \nu_k - l \cos \phi_k \omega_k \right) / \left( -(m_0 + m_1) \right) \\
\end{align*}
\]

By assuming that \( \Omega \) is an input to the HSA to generate a harmonic oscillation \( \eta(t) = A \sin(\Omega t) \) and \( \xi = 0 \), Equations (20)–(23) become system the equation yielding \( \phi, \omega, x, v \) as the outputs.

3.2. The Interactive Control Model for an HSAM and a Wire-Attached Mass

Figure 4 depicts a free body diagram for which the HSAM of a mass \( m \) is lifting a wire-attached mass \( M \). The viscosity friction between the inside of the tubular passage and the silicone spikes is expressed as a virtual damping effect. Let \( x_m \) and \( x_c \) be the displacements of the HSAM and the wire-attached mass, respectively. Let \( T \) be the tensile force of the wire. We know that:

\[
\begin{align*}
Mx_M &= T - Mg \\
m\ddot{x}_m + b \dot{x}_m &= -T + F_m \\
T &= k(x_m - x_M)
\end{align*}
\]

where \( g \) is the gravitational constant, \( F_m \) is the force generated by the HSAM, \( k \) is the spring constant, and \( b \) represents the virtual damping effect. Combining Equations (24)–(26) together, we can obtain an interactive control model as follows:

\[
\begin{bmatrix}
\dot{x}_m \\
\dot{x}_N \\
\dot{x}_M \\
\dot{x}_N
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 \\
-\frac{k}{m} & -\frac{b}{m} & \frac{k}{m} & 0 \\
0 & 0 & 0 & 1 \\
\frac{k}{M} & 0 & -\frac{k}{M} & 0
\end{bmatrix}
\begin{bmatrix}
x_m \\
\dot{x}_m \\
x_M \\
\dot{x}_M
\end{bmatrix} +
\begin{bmatrix}
0 \\
\frac{F_m}{m} \\
0 \\
-\frac{g}{M}
\end{bmatrix}
\]

Figure 4. The free body diagram to derive an interactive control model between the HSAM and the wire-attached mass pulled downward by gravity.

In Equation (27), all parameters can be known by practical measurement except \( b \). Suppose that the HSAM is not attached to the wire, then we know that:

\[
F_m = m \ddot{x}_m + b \dot{x}_m.
\]
If we have an actual measurement of the force, denoted by \( F \), which is generated by the HSAM, then \( b \) can be estimated by simple optimization in which the error \( e := \| F - F_m \|^2 \) is minimized. In other words, we can find \( b \) that allows the simulation result to yield the closest force value to the practical measurement. The minimization process will be discussed in Section 4.3 in detail.

The simulation using Equation (27) can tell us whether the wire-attached mass \( M \) can be lifted by the HSAM or not. Thus, it can be utilized to determine the number of HSAMs to generate enough force to manipulate an object.

4. Experiments

4.1. Preliminary Experiment

The parameters in Table 1 were measured by the following preliminary experiments. First, \( m_0, m_1, m_2 \) were measured by a digital scale (maximum resolution: 0.01 g). The length \( l \) of a spike was measured by a caliper. From the free diagram shown in Figure 3, the silicone spike was assumed to work as a torsional spring. Therefore, the stiffness constant \( c \) of the spike was estimated by linear regression based on the data in which a relationship between the applied force and deforming angle of the spike was measured.

Since Equations (20)–(23) are the discrete time dynamic model that takes the motor revolution speed \( \Omega \) as an input, we applied various voltage levels to a motor driver (Sabertooth 2 × 5, Dimension Engineering, Arkon, OH) to obtain the characteristic curve of the applied voltage level \( V \) to the revolution speed \( \text{rev/s} \). The characteristic curve for the employed motor showed 80 rev/s for 3.11 V and 200 rev/s for 7.37 V. When the applied voltage was less than 3.11 V or greater than 7.36 V, it caused the motor to rotate too slowly or to violate the safe operating range; hence, we did not test for those ranges.

4.2. System Identification to Estimate the Friction Coefficient \( \mu \)

In Table 1, the friction coefficient \( \mu \) is marked as “needs to be identified”. The idea of estimating it by the system identification process is that: (i) we measure the traveled distance of the HSA, and (ii) we find the \( \mu \) that best replicates the measured distance under the simulation. By following [21], we can assume \( \mu_+ = \mu_- \) by only considering \( \eta \) as an input. Therefore, we only needed to estimate one \( \mu \) value. The system identification process is as follows:

1. Apply various motor revolution speeds \( \Omega \) to a real HSA and record the traveled distance \( x \) after 5 s. \( \Omega \) was set to 80, 120, 160, and 200 rev/s. For each \( \Omega \) value, ten traveled distances were recorded. Then, the recorded distances were averaged after excluding the minimum and the maximum value.
2. Initialize \( \mu \) as an arbitrary value. Let \( \Delta t = 0.0001 \text{ s} \), and run the simulations using Equations (20)–(23). Store the outputs \( \phi_s, \omega_s, x_s, v_s \) (here, the subscript “s” is employed to distinguish the real measurement value from the simulation outputs).
3. Define the error function to be \( e := \| x - x_s \|^2 \), and find the \( \mu^* \) that minimizes \( e \).

4.3. Estimating the Virtual Damping Coefficient \( b \)

First of all, we operated the real HSAM and measured \( F \) by using a push-pull gauge (Digital Force Gauge, FGP-5, NIDEC-SHIMPO Corporation) under various \( \Omega \), i.e., 80, 120, 160, 200 rev/s. Next, we calculated \( F_m \) using Equation (28); in this case, we set \( \ddot{x}_m = \ddot{x}_s \) and \( \dot{x}_m = \dot{x}_s \), and \( \ddot{x}_s, \dot{x}_s \) were the outputs from the simulation in Section 4.2. Consequently, we can find the virtual damping coefficient \( b^* \) that gives us the minimum value of \( e := \| F - F_m \|^2 \).
4.4. Two Real Manipulating Applications

To demonstrate the feasibility of the proposed HSA and HSAM as a core component to implement robotic systems, especially to mimic the muscular-skeleton mechanism, an elbow manipulator and a robotic hand grasper were tested with the HSAM. Figure 5 depicts the location of the HSAM in the two applications. The HSAM was mounted at the exact same position of the muscles in the human forearm and the bicep brachii to mimic their behavior at a functional level.

![Figure 5. The two applications to demonstrate the feasibility of the proposed HSAM: (a) elbow manipulator; (b) robot hand grasper.](image)

5. Results

5.1. The Simulation Result of the HSA and the Estimation of the Friction Coefficient $\mu$

From the real measurement, the average displacement of the HSA was $x = 8.85, 57.14, 153.00, 231.28$ mm after applying a motor revolution speed of $\Omega = 80, 120, 160, 200 \text{ rev/s}$ for 5 s. Figure 6 shows the outputs $\phi_s, \omega_s, x_s, v_s$ from the HSA simulation when $\Omega = 80$, which resulted in $\mu^* = 0.259$. From the graphs in the left column, we can see that the spikes have an initial angle $\phi_0 = 30^\circ$ ($\frac{\pi}{6}$ rad) and vibrate within a range of $\phi_s \in [25.2^\circ, 34.8^\circ]$ (peak-to-peak: 9.6$^\circ$), then start taking-off after 2.5 s, finally reaching $x_s = 8.95$ mm, which is close to $x = 8.85$ mm after 5 s. Compared to this, Figure 7 is the simulation result under the condition of $\Omega = 160 \text{ rev/s}$ resulting in $\mu^* = 0.539$. In this case, the range of the spike vibration is $\phi_s \in [24.2^\circ, 36.1^\circ]$ (peak-to-peak: 11.9$^\circ$), and it starts taking off after 0.6 s, finally reaching $x_s = 153.21$ mm, which is close to $x = 153.00$ mm after 5 s.

From Figures 6 and 7, in addition to the outputs $\phi_s, \omega_s, x_s, v_s$, we can observe that the take-off time and the time to show a stable periodic locomotion also vary with respect to the input $\Omega$. In contrast to our expectation, different $\mu^*$ are obtained from the system identification process under different $\Omega$, which will be discussed in Section 5.4. The results from the HSA simulation and system identification are summarized in Table 2.

| $\Omega$ | 80  | 120 | 160 | 200 |
|---------|-----|-----|-----|-----|
| $\mu^*$ | 0.259 | 0.368 | 0.539 | 0.757 |
| $x$     | 8.85 | 57.14 | 153.00 | 231.28 |
| $x_s$   | 8.68 | 57.45 | 153.21 | 231.75 |
| $e$     | 0.0289 | 0.0961 | 0.0441 | 0.2209 |
5.2. The Simulation Result of the HSAM and Finding the Virtual Damping Coefficient $b$

For $\Omega = 80, 120, 160, 200$ rev/s, we had push-pull gauge measurement $F = 0.27, 0.63, 1.00, 1.28$ N. Figure 8 presents $x_s, \dot{x}_s, \ddot{x}_s$ and the corresponding $F_s = m_0\ddot{x}_s + b^*\dot{x}_s$. Under $\Omega = 160$ rev/s, $b^* = 26.6$ was found. Divided by the number of spikes $n = 140$, we can see that one spike has a damping coefficient of 0.190. Under $\Omega = 200$ rev/s, we have $b^* = 27.2$, which is similar to that under $\Omega = 160$ rev/s. For $\Omega = 80, 120$ rev/s, however, we have $b^* = 39.4, 34.4$, respectively, which are rather different from the previous ones. The results from the HSAM simulation and finding the virtual damping coefficient are summarized in Table 3.
Figure 8. Simulation result plots of $x_s$, $\dot{x}_s$, $\ddot{x}_s$, $F_s$ under the given conditions $\Omega = 160$ rev/s and $\mu^* = 0.539$.

Table 3. The summary of the experimental results in Section 4.3.

| $\Omega$ | 80  | 120 | 160 | 200 |
|----------|-----|-----|-----|-----|
| $b^*$    | 39.4| 34.4| 26.6| 27.2|
| $F$      | 0.27| 0.63| 1.00| 1.28|
| $F_s$    | 0.2701| 0.6296| 1.0011| 1.2821|
| $e$      | $1.0 \times 10^{-8}$ | $1.6 \times 10^{-7}$ | $1.2 \times 10^{-6}$ | $4.4 \times 10^{-6}$ |

Figures 9–11 present the simulation result from the interactive control model under $\Omega = 160$ rev/s and $F_m = F_s = 1.0011$ N (this is the same as $x = x_s$ and $m = m_0$). We used $k = 0.78$ N/mm, which could be read from the datasheet. For various $M$ values, we observe three cases: (i) the HSAM can lift $M = 90$ g (shown in Figure 9); (ii) the HSAM cannot lift $M = 110$ g (shown in Figure 10); and (iii) the HSAM is at equilibrium and stays still for $M = 102.5$ g (shown in Figure 11); hence, the maximum $M$ that can be lifted by the HSAM is $M = 102.5$ g.

Figure 9. Displacement ($x_m, x_M$) and velocity ($v_m, v_M$) plots of the HSAM and the wire-attached mass $M$ under $\Omega = 160$ rev/s and $M = 90$ g.
Figure 10. Displacement \((x_m, x_M)\) and velocity \((v_m, v_M)\) plots of the HSAM and the wire-attached mass \(M\) under \(\Omega = 160\) rev/s and \(M = 110\) g.

Figure 11. Displacement \((x_m, x_M)\) and velocity \((v_m, v_M)\) plots of the HSAM and the wire-attached mass \(M\) under \(\Omega = 160\) rev/s and \(M = 102.5\) g.

5.3. The Result of Manipulating Two Applications

Figure 12 shows an elbow manipulator application in which the HSAM mimics the function of the bicep brachii. The mass of the forearm part was 36.9 g, and we could determine that the forearm part could be lifted by one HSAM based on the result presented in Section 5.2. From Figure 12, we can see that the HSAM successfully lifted the forearm part at the rates of various speed levels.

Figure 12. The actuator module is applied for elbow manipulation. The mass of the lower arm was \(M = 36.9\) g, and \(\Omega = 160\) rev/s and \(\Omega = 200\) rev/s were applied for low speed and high speed manipulation, respectively.
Figure 13 shows a robot hand grasping application. The 3D-printed finger consisted of three segments, and the maximum mass of a single finger was 13.9 g; therefore, the total mass of the five fingers was less than 70 g, which is still under 102.05 g. However, since the silicone ligaments were inserted in each joint, the energy loss by its stiffness and damping was not negligible. Therefore, two HSAMs were employed for the thumb, index, and middle finger and the rest of fingers, respectively. The grasping task was performed successfully by the two HSAMs, as shown in Figure 13.

![Figure 13](image)

Figure 13. The actuator module is applied for robot hand grasping. The two actuator module grasped and released an object successfully. The total weight of the five fingers was \( M = 70 \) g, approximately, but there existed energy loss caused by the silicone ligaments between finger joints; therefore, we applied two actuator modules. \( \Omega = 160 \text{ rev/s} \) was applied.

5.4. Discussion

In Section 5.1, different \( \mu^* \) values were obtained by the system identification process with respect to the motor revolution speed \( \Omega \). Specifically, there was a large error between \( \mu^* \) values when \( \Omega = 80,120 \text{ rev/s} \) versus \( \Omega = 160,200 \text{ rev/s} \). This might be caused by substituting a signum function with a hyperbolic tangent function. Employing the hyperbolic tangent function imposes better continuity for the HSA system; however, its slope where the moving velocity of the HSA is zero might not be stiff enough. The error was also observed for estimating \( b^* \). Another reason might be caused by simplifying the elastic spike model to a rigid rod and torsional spring. In spite of some limitations, by adopting the estimated \( \mu^* \) and \( b^* \), the real measurement value could be replicated precisely during the simulations.

6. Conclusions

In this paper, we propose a hybrid soft actuator (HSA) inspired by a grass-spike, as well as a hybrid soft actuator module (HSAM). The design approach and dynamic models are presented for both the HSA and HSAM. Experiments are performed to estimate the friction coefficient and the damping effect by the system identification process. The estimated parameters are employed to replicate the real measurement by simulation, and the simulation results confirm that they can be replicated successfully. Two potential applications—an elbow manipulator and a robot hand grasper—are introduced to demonstrate the feasibility of the HSA and the HSAM, and both are performed successfully.

One of the future works should be refining our design approach. Specifically, the diameter of the HSA needs to be reduced, and the maximum force needs to be measured for the size-reduced version. If it generates enough force, then we need to check the possibility of encasing it. The system identification process to estimate the friction coefficient, as well as the damping effect should be refined to yield consistent values even under various motor revolution speeds. Lastly, for the encased HSAM, the control scheme should be modularized as well to be able to perform dexterous manipulations such as pencil gripping, pinch gripping, hand maneuvers, and so on.
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Abbreviations

The following abbreviations are used in this manuscript:

HSA Hybrid soft actuator
HSAM Hybrid soft actuator module

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