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Implementation of a Spring Backboned Soft Arm Emulating Human Gestures

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Abstract This study deals with the design of a spring backboned soft arm, which will be employed for generation of human gesture as an effective means of Human-Robot interaction. The special features of the proposed mechanism are the light weight and the flexibility of the whole mechanism by using a spring backbone. Thus, even in the case of collision with human, this device is able to absorb the impact structurally. The kinematics and the design for the soft arm are introduced. The performance of this mechanism was shown through experiment emulating several human gestures expressing human emotion and some service contents. Finally, this soft arm was implemented as the wing mechanism of a penguin robot.

Keywords: Soft Arm, Flexibility, Safety, Spring Backbone

1. Introduction

In the environment where human and robots coexist, robots should be designed and programmed in such a way that they are able to interact with human socially and physically in a safe fashion. The concept of HRI (human-robot interaction) has been evolved according to this demand.^[1]

Robots being developed with the background of HRI collect sensors' data, process the signals, recognize the information, and finally provide valuable services to human. As an example, the robot recognize the face of human by camera, detect the motion of human by a position sensor, and receive the intention of human by voice recognition. Combining those sensors' information, the robot decides the contents of the service, the sequence of service, and finally come to service action. Besides routine services such as many manipulation jobs and vocal service for human, facial expression or some gesture of robots help communication with human. Imitation of the facial expression^[2,3] and gesture^[4,5] of human are very important since it provides a familiar feeling when robots interact with human.

One of most critical issues of HRI is safety. Since the robot interacts with human physically or indirectly, a small position error or some programming error might cause crash between human and robot and resultantly damage the human body. Therefore, robot must have a soft arm structure that

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can absorb the shock or impact when contacting the human body. Design of a structurally soft robot hardware or precise control algorithm is required at the existence of such probable physical interaction.

Investigation of soft arm has drawn much attention recently. Kawamura, et al.^[6] developed a soft arm using pneumatic actuator. Bicchi, et al.^[7] investigated the tactic of fast and soft arm. Choi, et al.^[8] proposed a continuum mechanism applied to the design of soft endoscope. Park, et al.^[9,10] proposed compliant arms that have variable compliance at the robot joint or link. Khatib, et al.^[11] proposed a dual-actuator based feedback control algorithm to realize the soft arm. Yuki, et al.^[12] developed a soft manipulator with flexible joints using smart fluid and pneumatic cushion. Yoon, et al.^[13] designed a safe arm with MR-base passive compliant joints and viscous-elastic covering.

The objective of this study is to suggest a new soft arm for imitating human gesture, which is not only a means to enhance the effectiveness of HRI, but also enhances the safety by employing a soft arm structure. The special feature of this soft arm is the spring-backed structure, which allows structurally flexible characteristic. Even in the case of collision with human, this device is able to absorb the impact. The driving unit and the mechanism are separated. Thus, wide range of workspace can be ensured and a fast motion can be created because of small inertia of the system.

The section II deals with the kinematics of the soft arm. Its design will be described in the section III. Experimental implementation of diverse gestures is demonstrated in the section IV. Finally, we draw conclusion in the section V.

2. Kinematics of the soft arm

2.1 Structure

This study deals with the design of a soft arm with less number of actuator and emulate the motion imitating a couple of human gestures. Only three DC motors are used for this purpose. Fig. 1 shows the prototype of the soft arm. A spring is used as a backbone. The spring backbone is wrapped by acetyl

cylinders at a regular interval, which are connected by wires through three holes pierced in the cylinders. As shown in the figure, the arm is slimmed down from the proximal joint to the distal joint in order to reduce the weight of the arm.

Applying tensions to wires as shown in Fig. 2(b), the general motion of the soft arm can be represented as superposition of compression along the axial direction and bending in the global $X-Z$ plane. More specifically, Fig. 2(c) shows the deflection of one spring module caused by wire tensions. Note that because of the symmetry of the spring module, the length of the center line is the average of the lengths of the two sides.

Fig. 1. Structure of Soft Arm

2.2 Kinematics for a planar model

To find the end-position of the soft arm relative to the global reference coordinates, first, a planar model is considered. Fig. 2 shows the configuration of the planar model being bent in the global $X-Z$ plane where β_1 denotes the absolute rotation angle of the soft arm about the $\hat{Y}$ axis. As in Fig. 2(a), one spring and one link are defined as one node. Particularly, the dotted lines in Fig. 2(c) represent the locations of the virtual wires which are assumed to be located both on the inner surface and outer surface of the soft arm in the global $X-Z$ plane. It is noted that the end positions of the last node can be computed by summing up the lengths of wires that are assumed to be embedded along the center line of every node.

To compute the lengths of two wires for the given output angle (β_1), the positions (X_{pe} and Z_{pe}) of the last node relative to the node reference frame XOZ are obtained first. Then, the lengths of two wires are calculated.

Fig. 2. Side view of the soft arm structure

Since the soft arm is designed symmetric as in Fig. 1, deflection will occur uniformly throughout every module. Thus, analysis of one module could lead the kinematics for the whole mechanism. For our convenience, the module is numbered from the distal node to proximal node. Fig. 3 shows a module i of the planar model where lengths of the center lines (i.e. P and L_c^u) are assumed known.

Since the relative rotation angle of every module with respect to its neighboring module toward the wall is the same, the absolute rotational angle of each module about the $\hat{Y}$ axis (β_i , for $i = 1, \dots, N$) can be found as

$$\beta_i = \frac{N - (i - 1)}{N} \beta_1, \quad (1)$$

where N is the number of nodes. Thus, θ_a can be expressed as

$$\theta_a = 180^\circ - (\beta_i - \beta_{i+1}) = 180^\circ - \frac{\beta_1}{N}. \quad (2)$$

For the known value of θ_a , a is obtained from the geometry of Fig. 3 by using the cosine's law as below

$$a = \frac{1}{\sqrt{2}} (L_c^u - \frac{\Delta l}{N}) (1 + \cos \frac{\beta_1}{N})^{-\frac{1}{2}}, \quad (3)$$

where Δl is the amount of compression of the spring backbone as shown in Fig. 2(b).

Also, β_{i+1} can be found from Fig. 3 as

$$\beta_{i+1} = \beta_i + \theta_a - 180^\circ. \quad (4)$$

It is also noted that the proximal node is constrained to the wall such that $\beta_{N+1} = 0^\circ$.

Finally, the position of the distal point of the node i relative to the node $i+1$ is obtained as

$$W_i = P \cos \beta_i + a \cos \beta_i + a \cos \beta_{i+1}, \quad (5)$$

$$H_i = P \sin \beta_i + a \sin \beta_i + a \sin \beta_{i+1}. \quad (6)$$

Summing up Eqs. (5) and (6) for all nodes, the positions of the end-point in the reference coordinate can be obtained as

$$Z_{pe} = W_1 + W_2 + \dots + W_i, \quad (7)$$

$$X_{pe} = H_1 + H_2 + \dots + H_i. \quad (8)$$

2.3 Length of structure for the planar model

Now, θ_v denotes the angle change of the backbone spring module as shown in Fig. 2(c). The angle θ_v of every spring module has the following

Fig. 3. A node of the planar model

relation with β_1 as below:

$$\theta_v = \frac{\beta_1}{N \times 2}. \quad (9)$$

To bend the structure, the relationship between β_1 and the lengths of the pulling wires should be obtained. In the planar model, two wires are assumed to be embedded on the inner surface and on the outer surface of the backbone structure. In Fig. 2, L_c , L_s , and L_l , denote the length of the center line, the inner and outer boundaries of the planar soft arm model, respectively.

When the structure bends, L_s denotes the shortest length of the inner wire and L_l is the longest length of the outer wire as in Fig. 2(c). For the constant r and L_c^u , k is obtained as

$$k = r \sin \theta_v, \quad (10)$$

where r is the radius of the cylinder. Then, the lengths of L_s , L_c and L_l are obtained as

$$\begin{aligned} L_s &= N \left[P + \left(L_c^u - \frac{\Delta l}{N} \right) - 2k \right], \\ L_c &= N \times (P + L_c^u), \\ L_l &= N \left[P + \left(L_c^u - \frac{\Delta l}{N} \right) + 2k \right]. \end{aligned} \quad (11)$$

2.4 Kinematics for the spatial model

In the previous planar model, only one output angle β_1 was required to specify the position of the end-point of the robot or to find lengths of two wires which are assumed to be embedded on the inner and the outer surfaces of the soft arm. However, in the spatial model, one more output rotation parameter (γ) should be employed. The spatial model could be found by rotating the planar model (Fig. 2) by an

Fig. 4. The bent shape of the spatial model

azimuth angle γ about the global $\hat{Z}$ axis as shown in Fig. 4 where one such configuration of the spatial model is illustrated. Two output variables β_1 and γ represent the tilting angle of the soft arm and the orientation of the tilting angle, respectively. Note that this model only uses azimuth and tilt angles (β_1 , γ) in the tilt and torsion angle representation as shown below

$$Rot(\hat{z}, \gamma) Rot(\hat{y}, \beta_1) Rot(\hat{z}, -\gamma) Rot(\hat{z}, \sigma), \quad (12)$$

where σ represents the torsion angle and is assumed to be 0 in our model.

As shown in Fig. 4, when the end position of the soft arm in the planar model is known as $P_{pe}(X_{pe}, 0, Z_{pe})$, the global end positions $P_e(X_e, Y_e, Z_e)$ in the spatial model can be found as

$$\begin{bmatrix} X_e \\ Y_e \\ Z_e \end{bmatrix} = \begin{bmatrix} c_\gamma & -s_\gamma & 0 \\ s_\gamma & c_\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{pe} \\ 0 \\ Z_{pe} \end{bmatrix}. \quad (13)$$

2.5 Length of wire for the spatial model

The position of the soft arm structure is represented by the given angles of β_1 and γ . Particularly, because the rotation angle γ only transforms coordinates, it doesn't affect the length change of the structure. Thus, the length of the inner boundary (L_s) and the length of the outer boundary (L_l) in the spatial model are equal to ones in the planar model.

Now, the relationship between the two boundary lengths and the lengths of three wires (l_1 , l_2 and l_3) is obtained from the bending geometry of Fig. 5 and the cross-sectional area of the spring backbone structure given in Fig. 6.

In Fig. 5 and Fig. 6, the lines connecting three points, p_1 , p_2 , and p_3 denotes the bending plane. From the cross-sectional geometry, θ_{l1} , θ_{l2} , and θ_{l3} which represents the location of three wires, respectively, are expressed in terms of γ as follows

$$\theta_{l1} = \gamma, \quad (14)$$

$$\theta_{l2} = 120^\circ - \gamma, \quad (15)$$

$$\theta_{l3} = 120^\circ + \gamma. \quad (16)$$

It is noted that the amount of deformation along the axial direction of all elements on the dotted line

Fig. 5. Bending geometry

Fig. 6. Cross-sectional area of the spring backbone structure

perpendicular to the bending plane as shown in Fig. 6 is equal. Thus, the lengths of three wires can be computed as follows. In Fig. 2(c), the lengths of L_s and L_l can be expressed in terms of their unit lengths (L_s^u and L_l^u) such as

$$L_s = N(L_s^u + P), \quad (17)$$

$$L_l = N(L_l^u + P). \quad (18)$$

Then, L_s^u and L_l^u are related as

$$\frac{L_s^u}{\rho} = \frac{L_l^u}{\rho + 2r} \quad \text{or} \quad \rho = \frac{2rL_s^u}{L_l^u - L_s^u}. \quad (19)$$

Noting that in the bending plane of Fig. 6, deformations of all points on each dotted line (e.g., M_1, M_2, M_3) are the same, the unit length l_i^u of the wire l_i is related to the shortest inner length as

$$\frac{L_s^u}{\rho} = \frac{l_i^u}{\rho + r(1 - \cos \theta_{di})} \quad \text{for } i = 1, 2, 3. \quad (20)$$

Thus, from (19) and (20), the unit length l_i^u of the wire l_i can be expressed as

$$l_i^u = L_s^u + \frac{1}{2}(L_l^u - L_s^u)(1 - \cos \theta_{di}) \quad \text{for } i = 1, 2, 3. \quad (21)$$

The relationship between l_i^u and the length l_i of the i -th wire can be expressed as

$$l_i^u = \frac{l_i - NP}{N}, \quad i = 1, 2, 3, \quad (22)$$

where P is the length of one cylinder module. By using (17), (18), (21), and (22), the length l_i of the i -th wire is obtained as

$$l_i = L_s + \frac{1}{2}(L_l - L_s)(1 - \cos \theta_{di}) \quad \text{for } i = 1, 2, 3. \quad (23)$$

When the deflection due to the compression of the spring along the axial direction, denoted as Δl , is taken into account, the length of each of three wires can be found as

$$l_i = L_s + \frac{1}{2}(L_l - L_s)(1 - \cos \theta_{di}) - \Delta l. \quad (24)$$

Thus, Δl_i denoting the total length change of each of three wires l_i can be found as

$$\Delta l_i = L_c - l_i \quad \text{for } i = 1, 2, 3. \quad (25)$$

which is the amount of the required length change of wires for the given output variables ($\beta_1, \gamma, \Delta l$).

3. Design of the soft arm

3.1 Design of a Soft Arm

Figure 7 shows the design concept of the proposed soft arm, which consists of an arm part and a driving part. The arm is designed by assembling a spring and hollow plastic cylinders. Three wires

Fig. 7. The design concept of the soft arm

penetrate into the holes located at the cross sectional area of the cylinders.

The driving unit adapts a linear actuator as the basic unit, which consists of a TM screw (M8; triangular gear with pitch 1.25mm) and a DC motor with encoder. The stroke of the screw is 35 mm. Three of this driving unit are assembled and placed 120 degrees apart. A pulley is employed to guide the pulling wire to the actuator and a photo sensor is used for home positioning. The arm comes to action when pulling the three wires simultaneously.

3.1.1 Arm structure

The soft arm is designed to have a soft structure when contacting to environment or human. The spring mechanism plays such a role. Also, in order to prevent bucking of the whole mechanism, an extension spring or a flexible tube line is inserted at the center of the arm.

Figure 8 shows the detail of the soft arm. It is designed by assembling several springs and plastic cylinders in a successive manner. As the length of the arm becomes longer, the whole mechanism deflects due to its own weight. Thus, we employ a light-weight cylinder made of acetyl whose specific weight is about 1.4. Also we made several holes at the cross section of the cylinder to reduce the weight as shown in Fig. 9.

Furthermore, the weight could be reduced by slimming down the arm from the proximal node to the distal node as shown in Fig. 8. Based on this design, Table 1. shows the final weight of each cylinder.

Fig. 8. Structure of the arm

Fig. 9. Cross section of cylinder

Table 1. Weight of each cylinder

node	1	2	3	4	5
Weight(g)	16	14	12	10	8

- Spring

The joint connecting two adjacent plastic modules is made by a coil spring so that the arm is able to bend when pulling the three wires. Table 2 shows the specification of springs. The diameter of each spring is decided properly according to the size of each node. The spring constants of all springs are the same.

Table 2. Specification of springs

Joint	K (N/mm)	Diameter (mm)	Thickness (mm)
1	2.9	18	1.8
2	2.9	18	1.8
3	2.9	16	1.7
4	2.9	16	1.7
5	2.9	13	1.4

Table 3. Distance from the shoulder to each node

	d1	d2	d3	d4	d5
Distance(mm)	41.5	94.5	147.5	200.5	253.5

- Driving wire

The driving wire plays the role of driving the whole mechanism as well as connecting the plastic cylinders and the springs. The diameter of the stainless wire is 0.8mm and its maximum tensile load is about 0.588~0.667 kN ($\approx 60\sim 68$ kgf). The three wires are placed 120° apart so that the soft arm can be steered in all directions.

3.1.2 Analysis of the pulling load of wire

In order to analyze the pulling load of wires, Fig. 10 depicts the moment created by the weight of the plastic cylinders.

Summation of moments due to all nodes is denoted as

$$M_a = M_1 + M_2 + M_3 + M_4 + M_5 = \sum W_i \cdot d_i. \quad (26)$$

According to the weight and the distance information of each node from Table 2 and 3, the total moment that should be supported at location of the shoulder is calculated as

$$M_a = 9.79 \text{ kg} \cdot \text{mm}. \quad (27)$$

This moment should be resisted by the pulling load of the wire (Fig. 11). When the moment due to the weight of the arm is equal to the resisting moment due to the pulling wire, the soft arm maintains its shape without deflection due to its weight. Now, the moment due to pulling wire is denoted as

$$M_w = f_w \cdot r, \quad r = 14.7 \text{ mm}, \quad (28)$$

where f_w and r , respectively, denote the pulling load and the location of the wire from the center line of the spring. Resultantly, the pulling load of the wire preventing the deflection of the arm is calculated as

$$f_w = 0.67 \text{ kg}_f \quad (= 6.5 \text{ N}). \quad (29)$$

Fig. 10. Moment due to the weight of cylinders

Fig. 11. Moment due to the pulling wire

- Backbone

In addition to the deflection of the soft arm due to the weights of all nodes, there exists an internal deflection (i.e., a buckling phenomenon) of the soft arm due to the mechanical coupling among modules. In order to prevent such internal deflection, a spring backbone is inserted into the center position of the spring. Fig. 1 shows that the whole structure does not have such deformation due to the additional backbone spring.

3.1.3 Actuator sizing

- Torque

The torque required for the system operation can be derived from the screw mechanics depicted in Fig. 12.

In Fig. 12, W , P , μ , λ , T , and d_e denote the axial direction weight (kg_f), the radial force of screw (kg_f), the friction factor of the surface of screw, the lead angle, the required torque ($\text{kg}_f \cdot \text{mm}$), and the efficient diameter of screw, respectively.

Neglecting the dynamics of the system, the force equilibrium equation of the screw is given by

$$P \cos \lambda - W \sin \lambda = \mu (P \sin \lambda + W \cos \lambda). \quad (30)$$

Reformulation in terms of P gives

$$P = W \frac{\mu \cos \lambda + \sin \lambda}{\cos \lambda - \mu \sin \lambda}. \quad (31)$$

Since $\mu = \tan \rho$, we have

$$P = \frac{W \tan \rho \cos \lambda + \sin \lambda}{\cos \lambda - \tan \rho \sin \lambda} = W \tan(\lambda + \rho). \quad (32)$$

Eq. (34) is simplified, by using $\tan \lambda = \frac{P}{\pi d_e}$, as

$$P = W \left(\frac{p + \mu \pi d_e}{\mu \pi d_e - \mu p} \right). \quad (33)$$

Thus, for the given W , the moment T of the screw is calculated as

$$T = P \frac{d_e}{2} = W \frac{d_e}{2} \tan(\lambda + \rho) = W \frac{d_e}{2} \cdot \frac{p + \mu d_e}{\pi d_e - \mu p}. \quad (34)$$

The pulling load (W) of the wire to prevent the deflection of the soft arm was 0.67 kg . Then, the minimum torque to drive the soft arm for a given specification ($W : 0.67 \text{ kg}$, $\mu : 0.15$, $P : 1.25 \text{ mm}$, $d_e : 6.8 \text{ mm}$ (M8)) is calculated as $0.35 \text{ kg} \cdot \text{mm}$. However, considering the dynamic inertial load of the soft arm, energy loss due to friction, and the motor efficiency, the actual actuator size should be decided greater than this result.

Fig. 12. Screw mechanics

- Speed

Another important factor in the decision of actuator is the speed. For the given maximum operational speed of the soft arm, the maximum rpm of the motor is decided.

The design procedure is as follows. First of all, estimate the fastest motion of the arm such as the surprise motion. Assuming that the time for the fastest motion is set as 1 second, the driving unit should be able to move the whole stroke 35mm of the screw within 1 second, too. Since the pitch of the screw is 1.25mm, the RPS (Revolutions per Second) of the motor can be calculated as

$$RPS = \frac{Stroke}{pitch} = 28. \quad (35)$$

Then, the RPM (Revolutions per Minute) of the DC motor is converted as 1,680 RPM. Same as the motor torque, the RPM should be decided with consideration of the safety factor.

- Motor Specification

Based on the above analysis on the motor torque and the speed, a DC motor (Model : IG-32PGM, D&G Motors) was selected. Considering the motor efficiency, the safety factors in terms of the motor torque and the speed are calculated, respectively, as

$$S_{torque} = \frac{2.48}{0.35} \times (0.85) = 6.02, \quad (36)$$

$$S_{speed} = \frac{5090}{1650} \times (0.85) = 2.61. \quad (37)$$

A large safety factor is given to the torque size since the system should compensate for the dynamic inertial load due to the motion of the soft arm.

4. Experimental Works

4.1 Bending Motion of the Soft Arm

Figure 13 shows the results of simulation and experiment when the soft arm is bent to 45° and 90° on the X-Z and the Y-Z plane, respectively. Table 4 shows the comparison of the simulation result and the experimental result. The error is caused by non-uniformly deflection of each module and deflection due to gravity. The error can be minimized by

kinematic calibration of the mechanism. However, the purpose of the proposed mechanism is an emulating of human gestures, not a precise positioning. Thus, using the control algorithm of the soft arm, we perform experiments in which the soft arm emulates several human gestures expressing human emotion and some service contents.

Fig. 13. Results of simulation and experiment

Table 4. Comparison of simulation and experimental data

Motion		Position	Simulation	Experiment
X-Z plane	$\beta_1 = 45^\circ$	X	109.23 mm	50 mm
		Z	225.57 mm	243 mm
	$\beta_1 = 90^\circ$	X	182.79 mm	130 mm
		Z	143.13 mm	205 mm
Y-Z plane	$\beta_1 = 45^\circ$	Y	-109.23 mm	-107 mm
		Z	225.57 mm	230 mm
	$\beta_1 = 90^\circ$	Y	-182.79 mm	-163 mm
		Z	143.13 mm	170 mm

4.2 Emulation of Human Gestures

Figure 14 shows the picture of a dual soft arm. Using this device, we would like to emulate several human gestures expressing human emotion and some service contents. The driving unit and the mechanism are separated. Thus, a wide range of workspace can be ensured and a very fast motion can be obtained because of the small inertia of the arm.

Fig. 14. Dual soft arm

4.2.1 HRI by gestures expressing emotion

Figure 15, 16, 17, 18 denote the gesture of the dual soft arm expressing “angry”, “delight”, “sorrow”, and “surprise” emotion, respectively.

Fig. 15. Gesture expressing “angry”

Fig. 16. Gesture expressing “delight”

Fig. 17. Gesture expressing “sorrow”

Fig. 18. Gesture expressing “surprise”

4.2.2 HRI by gestures expressing several service actions

Figure 19 and Fig. 20 show the gesture of the dual soft arm denoting “shaking hands” and “direction guide service”, respectively.

Fig. 19. Shaking hands

Fig. 20. Direction guide service

4.2.3 Soft characteristic of the soft arm

The special feature of this soft arm is the spring-backboned structure, which allows structurally flexible characteristic. Even in the case of collision with human, this device is able to absorb the impact. Fig. 21 shows that the soft arm deflects without giving damage to the human when it collides with the human body.

Fig. 21. Flexible soft arm

4.3 System Implementation

The developed soft arm is implemented as the arm structure of a character service robot. The soft arm is used as the wing of the penguin service robot. This robot will be employed for the purpose of storytelling to young children. Fig. 22 shows gestures expressing the four kinds of emotion and several service actions of the penguin service robot.

5. Conclusions

The contribution of this study is the suggestion of a new soft arm with a spring backbone. The driving

unit and the mechanism are separated. Thus, a wide range of workspace can be ensured and a fast motion can be created because of the small inertia of the arm. Even in the case of collision with human, this device is able to absorb the impact due to the spring backboned structure. This soft arm can be employed as a means of HRI by emulating gestures expressing several kinds of emotion. This soft arm mechanism was successfully implemented as the wing structure of a penguin service robot.

Fig. 22. Gestures expressing emotions and several service actions of the penguin service robot

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