A Flexible Spine Human-Form Robot
— Development and Control of the Posture of the Spine —

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Abstract

In this paper, the development of a robot which has a flexible spine is presented. By embedding a multi-DOF (degree of freedom) soft structure into a robot body as a spine, the robot can increase its ability to absorb shock and the ability to work in various environments such as narrow places or humans' fields, and its motion could be more natural. The developed full-body human-form robot has a five-jointed flexible spine. Each joint (vertebra) has 3 DOFs. Between each two vertebrae is a “disk” made of silica one rubber. The spine is controlled by eight tendons, whose tensions can be controlled using tension-sensors and locally distributed microcontrollers. This paper describes the development of the flexible spine and the control of the posture of the spine and body.

1 Introduction

Recently there have been developed a lot of humanoid type robots [1, 2, 3]. However, we often feel that the motions of the robots are restricted because of the rigid torso. The flexibility of the torso will be a key to the next stage of robotics research. The flexible torso (spine) will be needed to achieve human-like motions, and also to realize the sufficient and efficient DOFs for the practical use. On the other hand, the variability of the flexibility is important. With the variability, robots can change the flexibility according to the situation. The goal of this research is to develop a robot which has a variable flexible structure like a creature’s spine, clarify control methods of the spine and whole body, and apply the robot to various tasks such as in narrow places or in humans’ field.

To achieve the goal, it is necessary to design a spine structure with variable flexibility and many DOFs. It is also necessary to discuss how to control the structure. This paper describes the development of a variable flexible spine structure and a fullbody human-form robot equipped with the spine, the proposal of a control method of the spine, and some experiments using the fullbody robot.

2 Flexible Spine Human-Form Robot

Almost all of the human-form robots ever developed were so rigid that there was a danger for human to be hurt. The research on flexible robots[4] or multi-joint-structure robots[5, 6] have not been applied to the torso of humanoid. On the other hand, there have been some researches on embedding a movable mechanism in the torso (trunk) of human-form robot[7], these robots’ torso can rotate around only one concentrated axis and they do not have any variable flexibility. We propose a robot which has variable flexible structure in the torso (spine). By embedding a soft spine into the torso, robots will have several characteristics below.

The increase of DOF of the torso: A flexible spine has more DOFs than a rigid torso. It means that the movable area of the robot or of the arms would be expanded. It also means that, by using the increased DOFs, motions of the robot can be more efficient compared to a rigid torso. For example, in the motion to rise the upper body from the floor, a flexible spine robot can move each joint one by one from the neck joint to the hip joint. This procedure is more efficient than rising the upper body from the floor using only hip or crotch joint. Furthermore, the motions of the flexible spine robots could be nearer to natural (human-like) motions.

Softness (flexibility): By the softness of the spine, the robot can absorb the shock, and it has a safety at the physical contact with a human or objects.

Variable flexibility: The spine of human-form robots has to support the upper body when needed. In
another situation, the robot may have to adapt to the outer force put by human. When the robot needs to lift up a heavy object from the floor, the spine should be comparatively hard. The variability of the flexibility is very important.

3 Structure of the Flexible Spine

3.1 Series Ball-and-socket Joints and Silicone Rubbers

Fig. 1 shows the structure of the flexible spine we developed. Each joint is a ball-and-socket joint and has 3 DOFs: roll, pitch, and yaw rotations. The whole spine has 5 joints and the total number of DOFs is 15. There is a part made of silicone rubber between each two joints. Each rubber acts as a “disk” in the human’s spine. The height of each rubber is slightly larger than the distance between two neighbor joints. Therefore, the rubber is put pressure in advance.

At the lower and upper ends of the spine, there are two parts like a clavicle and a pelvis. 8 motors to pull tendons are placed inside the parts. Each tendon is nearly parallel to the axis of the spine and is bound obliquely from the clavicle to the pelvis and vice versa (see Fig.9). This spine structure is theoretically uncontrollable because the number of structural DOF is larger than that of actuators. Why the spine keeps its stability is that there are forces of the elasticity of rubbers. The posture of the spine depends on the balance of rubbers’ forces, tendons’ tensions, and outer forces.

The structural movable range of each joint is about $\pm 18^\circ$ in roll and pitch, and $\pm 180^\circ$ in yaw. With the disks, the range in yaw-axis is restricted to about $\pm 18^\circ$.

Therefore total rotational movable range of the clavicle observed from the pelvis is about $\pm 90^\circ$ in roll, pitch and yaw angle. The translational movable range along two horizontal axes (X and Y) is calculated by

$$\pm \frac{l}{3} (\sin 18^\circ + \sin 36^\circ + \sin 54^\circ + \sin 72^\circ + \sin 90^\circ)$$

where $l (~150[mm])$ is the distance between the clavicle and the pelvis(Fig.5). Therefore total translational movable range of the clavicle observed from the pelvis is about $\pm 110[mm]$ along the horizontal axes. The range along vertical axis is about $+0 – 70[mm]$, calculated by replacing $\sin x$ by $(1 – \cos x)$ in the above formula.

3.2 Tendons with Tension Sensor

3.2.1 Actuating spine using tendons

Several ways to change the posture of the multi-joint spine can be considered. A way is actuating each joint directly. In the way, variable flexibility may be embedded to each joint[8]. Another way is using tendons. We’ve chosen tendons because actuating each joint needs more torque. The lowest joint of the spine has to exert quite much torque.

Arrangement of tendons is decided by considering also reducing the maximum torque. When tendons are placed along the structure like snake[3] or elephant-trunk[6], necessary tensions are larger than when tendons are placed apart from the spine like human. Therefore the tendons of the spine of the developed robot are fixed at the ends of pelvis and clavicle.

3.2.2 Tension sensors

Needs of tension sensor The posture of the spine is determined by balance of rubbers’ elastic pressures and tendons’ tensions, as described in 3.1. Therefore tension sensors of tendons are essential. Besides, the tension sensors can be useful when adjusting tendons to the neutral positions. Tendons often stretched and neutral positions of them are often shifted.

The structure of the developed tension sensor Fig.2 shows the structure of the tension sensor. A force sensor (FSR:force sensing register) and a piece of urethane are put between two parallel aluminum plates. The pressure put on the sensor depends on the tension of the tendon, seen in Fig.3. The sensor is nonlinear and the stretch is limited to a certain value. A preferable characteristic is that, the larger the tension becomes, the less the resolution of the sensor becomes. The relation between the tension ($F$) and the force on the force
Figure 2: the structure of developed tension sensor

sensor ($f$) is represented by the equation below.

$$f^2k^2 = (f^2 + f^2)(b - f/k)^2$$

Calibration of the tension sensor Because the tension sensor is nonlinear, we calibrated the relation between the actual tension (measured by a force gauge) and the output of the tension sensor. Fig. 4 shows the relation. A tension is calculated by linear interpolation from the measured values. We suppose this tension sensor can be used at least to the calibration of the lengths of tendons and adjusting the balance of the tensions.

3.3 The Flexible Spine Robot “Cla”

We developed a fullbody human-form robot named “Cla” equipped with the variable flexible spine mentioned above. The left side of the Fig. 5 shows the arrangement of DOF, and the right side shows the front and side view. The length is 51 [cm], and the weight 2.7 [kg]. The number of actuators is 26, and the number of structural degrees of freedom is 33. The joints of two arms and two legs are directly rotated around the joint-axes by DC motors, and the joints of the torso are driven by 8 tendons which are pulled by 8 DC motors through pulleys. Four motors are placed in the clavicle and the four other motors are in the pelvis.

All motors are controlled by eight onboard processors. All the processors are connected together to an onboard-LAN[9, 10], which is based on the IC-bus protocol[11], a multi-IC serial communication bus designed by Philips. The remote host makes calculations for control mentioned below and communication with the hub of onboard network is done using RS232C.

4 Control of the Flexible Spine

4.1 Changing the Posture

We have constructed a geometric model of the robot, which is described in an object oriented Lisp, EusLisp[12]. In the model, all parts of the robot connected by joints have 3D coordinate systems. Each coordinate system, described as an instance of ‘cascaded-coords’ class in the lisp, has the pointer to its parent coordinate system, and has a rotation matrix and a translational position vector, represented by the parent coordinate
system. Every instance of the class can extract the rotation matrix and position vector represented by the world frame. The position to which a tendon is fixed and the position of the pulley are also instances of the ‘cascaded-coords’ class, whose parents are the coordinate systems of the pelvis part or the clavicle part. Each coordinate system can be rotated around an axis (vector) or moved translationally, and then all descendants are automatically rotated or moved.

The spine is described as series ball-and-socket joints, each of which has three degrees of freedom: roll, pitch and yaw. We can change the posture of the spine by rotating each joint in the axes. By assuming that each joint rotates by the same amount, we can designate the posture of the whole spine using the values of roll, pitch, and yaw angle. When a posture is given, the length of each tendon is calculated by measuring the distance from the fixed position to the position of the pulling pulley. The interferences of wires are not taken into account in this model. How we avoid the problem of the interference is described in 4.3.

Though the inverse kinematics is easily solved (if without regard to interferences), the kinematics is not. The lengths of the tendons can be calculated when a posture is given. However, even if the lengths of all the tendons are provided, the posture cannot be estimated; there are even impossible combinations of the lengths. From another point of view, even if the lengths of eight tendons are all controlled to the lengths calculated from a posture in the model, the posture of the real robot does not always match the posture in the model. The posture is determined by the balance of the forces of tendons, rubbers, gravity and disturbances.

4.2 Control Modes

We have implemented several kinds of control modes of tendons.

4.2.1 Tendon length control mode

In this mode, the information from tension sensors is not used. The target of control is the value of the rotary encoder of each motor, which drives a pulley pulling each tendon. The gains (proportional and differential) can be designated. The posture of the spine can be controlled using this mode; by controlling the tendon so that the length be the same as that calculated by the model described in 4.1.

4.2.2 Tendon length control mode with tension limitation

This mode is a mode which is added the limitation of the tension to the above mode (4.2.1). The gains (pro-

![Figure 6: Block diagram of tension control by software](image)

portional and differential) and the tension limit can be designated. When the tension of a tendon exceeds the limit, the output signal to the motor is stopped. The motor has a little back-drivability. The significance of this mode is as follows:

**Safety (fail safe):** Tendon becomes passive when large force is detected, e.g. a case of impact. Or, at an experimental phase, this mode can avoid extreme postures.

**Teaching a posture:** Because the degrees of passive freedom at the torso is large, it is not easy to recognize the expression of the posture of the torso intuitively using the model on computer (4.1). Direct teaching or interactive teaching is more convenient. This mode can be used for the teaching. If all the tension limits are comparatively small and the target lengths of the tendons are short, then loose tendons are pulled and the motor power of tight tendons are stopped and pulleys of the tight tendons gradually rotates passively. Using this procedure, we can directly adjust the posture. One thing we should mention is that, it is not possible to distinguish the force by human and the force by gravity. Therefore, it can retain a posture only when each tension is less than the back-drivable force of each motor.

**Neutral position calibration:** By adjusting the posture by hands in the same condition as the previous item, and setting the lengths as neutral, we can easily calibrate the neutral position.

4.2.3 Tendon tension control mode

Fig 6 shows the block diagram of tension control by software of onboard processors. The input is the target tension and the output is the motor current. In order to avoid the vibration, there is an insensitive area ($\pm \Delta T_{hr}$) around the target tension ($T_{rf}$). The target tension ($T_{rf}$), the control gains (proportional and differential), and the insensitive area parameter ($T_{hr}$) are all adjustable from the upper software layer. Tension control enables the robot to adapt to the environment, and be relatively harmless. There’s another aspect we’d
like to mention. When all tendons are controlled to the same tension, antagonistic pairs of tendons placed at the both sides are in equilibrium, and the forces on the spine can be considered as only the elastic forces of rub-
ers and gravity. By the elastic forces of rubber, the spine tends to be settled in the neutral posture. By adjusting the distribution of the target tensions of ten-
dons, we can let the spine tend to be settled in other postures. If we can calculate the forces of rubber in a certain posture, we can control the posture of the spine by controlling the tensions so as to balance with the rubber's forces. This discussion is valid only if no disturb ance force exists.

4.2.4 Tendon spring mode

Fig.7 shows the diagram of software-spring mode.

In this control mode, there’s a double loop. The inner loop is tension-control loop, same as described in 4.2.3. The target tension \( (T_{ref}) \) is determined by the equation below:

\[
T_{ref} = (L_0 - L) \times K_f
\]

In the equation, \( L_0 \) indicates the natural length of the imitated spring, \( L \) the current length, and \( K_f \) the spring coefficient. \( W \) can designate \( L_0 \) and \( K_f \) from software. \( W \) can also designate the parameters of PD controller of the inner tension-control loop in Fig.7.

By using this mode, w e have realized the dynamical change of the flexibility of the spine, by changing the spring coefficient \( K_f \). When \( K_f \) is smaller, the spine is softer, and when larger, more rigid. Fig.8 shows the experiment using only the upper body of the robot. In the left one, the spine is softer (using smaller \( K_f \)), and in the right one, it is more rigid (larger \( K_f \)). The control cycle is 1 millisecond.

4.3 Spine Posture Control Experiment

By calculating the necessary lengths of tendons using the geometric model (4.1), we’ve done several expe-
ments of the spine posture control. The left of Fig.9 is a view of the computer model, and the right one is the real robot. If the tendons of the real robot are precisely controlled to the lengths generated by the model, then the combination of tendon-lengths might be impossi-
ble; for there might be some interference in tendons or interference between tendons and the robot body. In case this occurs, the tendons whose relative lengths are larger than the neutral length should be controlled in the tension control mode (4.2.3). Other tendons are controlled in the length control mode (4.2.1). Fig.10 shows various poses by the developed robot “Cha”.

The maximum velocity of pulling a tendon depends on the maximum velocity \( \omega_m = 263.7[\text{rpm}] \) with gear of the motor and the radius \( r = 3[\text{mm}] \) of the pulley; \( 2\pi r \times \omega_m / 60 = 82.8[\text{mm/s}] \). The difference between the wire-length of neutral pose and that of maximum bending pose is 74.2[mm] (roll), 12.5[mm] (pitch), and 36.7 (yaw). Therefore any movement from neutral posture can be done in one second. The difference of the lengths by roll movement and pitch movement is due to the shape of the clavicle and the pelvis: the parts are long from side to side. The developed system includes an interpolation function of the reference of motor angle. The interpolation is based on minimization of jerk[13].
5 Summary and Conclusions

A fullbody human-form robot which has a flexible spine structure is realized. The flexibility of the spine is variable by tension sensors and control software. Several kinds of control methods are proposed and some experiments on changing the flexibility of the spine and changing the posture using a geometric model and a control mode. We have pointed out the characteristics and advantages of being equipped with a variable flexible spine; the increase of DOF of the torso, flexibility and its variability. A way to realize a variable flexible spine is also presented.

The problems needed to be solved are, modeling or calibrating the rubbers' force according to the posture, controlling the posture with tension control, whole-body motions by cooperation of the spine and the limbs, shock absorbing motions, increasing tendons (muscles), especially attaching tendons which are connected to the middle of the spine, and so on.

Acknowledgments

This research has been supported by "Research for the Future" Program of the Japan Society for the Promotion of Science (JSPS-RFTF96P00801).

References


