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Design of a Biomimetic Spine for the Humanoid Robot Robota*

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***Abstract*— This paper presents a prototype of 3 degrees-of-freedom articulated spine for the doll-shaped humanoid robot *Robota*. This work follows an approach that emphasizes the need for a high human-likeliness in both the external features of the robot and in the kinematics of its motions to enhance human-robot interactions. The design of a spinal cord for our humanoid robot satisfies both criteria in providing offering a smooth human-like parallel means of bending forward and sideways.**

Index Terms— **Bio-mimetic Spine, Humanoid Torso**

I. Introduction

The Robota project designs a series of biomimetic humanoid robots [1][2]. Since 1998, Robota has being used as part of studies with autistic children [3], [4]. These studies compare the effect that human-like features may have on the interest that children with autism show in interacting with another agent. Thus, expressing human-like characteristics, both in the robot's body features and in the robot's behaviors, has been for long a key constraint in the design of Robota.

The current prototype of Robota, which we describe here (see Figure 1), will find an application in a variety of work on human-robot interactions, conducted at our laboratory, see, e.g. [5], [6]. In these, we study the means by which one may endow the robot with human-like motions through imitation learning. A high resemblance between the human body and that of robot simplifies largely the so called "correspondence problem" [7], in which the motion of the human must be let to correspond to that of the robot. So far, our work has concentrated on teaching the robot simple manipulatory motions involving the two arms. The design of a flexible spine for the Robota robot will allow us to extend this work to teaching motions involving the whole torso. By requiring that the spine flexes the same way as that of the human body along the pan and tilt directions of motion, we ensure a good correspondence between the human motions and that of the robot during kinesthetic teaching (such as that done on our Fujitsu HOAP-2 robot, see Figure 2).

In [8], we presented a prototype of a 7 degrees of freedom arm (DOF) and of a 3 DOFs pair of eyes for an extended version of Robota. In this paper, we present the recent development of an articulated spine to endow the robot with human-like motions of its torso. We report on the various stages of design, taking the time to describe solutions that, although feasible in theory, appeared unpractical when implemented. Although this is unusual, the literature tending to report usually on final working prototypes only, we believe that, in some cases, it is also instructive to report on unfeasible solutions, especially when those can be proved wrong only when created.

II. State of the Art

The design of humanoid robots form a growing body of robotics research. However, the vast majority of those works follow a relatively classical approach in the design of the actuators of the robot's torso, by locating those serially at the level of the waist. Examples of such robots include Honda ASIMO [9], Sony Q-RIO [10], Fujitsu HOAP-1&-2 and HRP-2P [11] developed by the Kawada Industries. All of these have either one or two DOFs, whereas the humanoid robot WABIAN [12] from Waseda university, COG [13] at MIT and ARMAR [14], a humanoid robot developed at the Karlsruhe university have three DOFs.

There exists, however, a few solutions that follow more of a biomimetic design. For instance, the CLA and KENTA [15], [16] robots, developed at Tokyo University, offer two solutions of articulated spine, that mimics the human spine. For recall, the human spine consists of 24 vertebrae that are stacked on top of each other. Between each vertebra is a soft, gel-like cushion called a disk which play the role of shock-absorber and keeps the bones from rubbing against each other. Each vertebra is held to the others by groups of ligaments. The spinal column also has joints called facet joints. The facet joints link the vertebrae together and give them the flexibility to move against each other. The average range of motion are $\pm 30°$ for the flexion-extension, $\pm 40°$ for adduction-abduction and $\pm 30°$ for the rotation.

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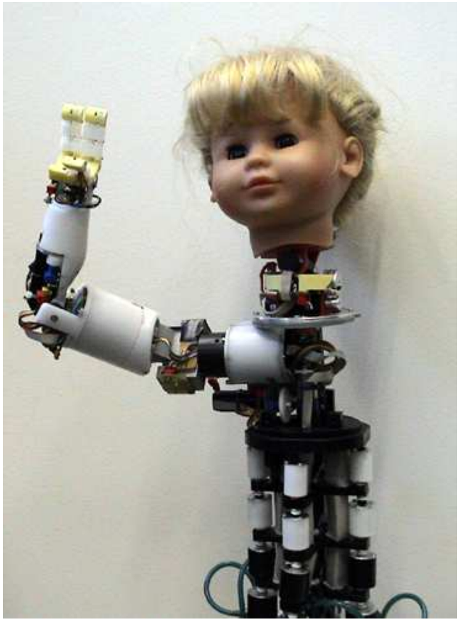

Fig. 1. Current prototype of the new Robota. It encompass a 6 DOFs arm with 1 DOF gripper, 3 DOFs pair of eyes mounted with 2 cameras, 3 DOFs neck and 3 DOFs spinal cord. In a latter stage, the prototype will be embedded in a plastic coating similar to that of commercial doll, , see Figure 3, to ensure that all mechanical parts are hidden.

The spine of the robot KENTA is constituted of 10 joints with 3 DOFs per joint, so as to mimic the assembly of vertebrae in the human spine. 40 actuators are used to control the spine (See [15]). In the robot CLA, the spine consists of five flexible joints, separated by a rubber layer. The rubbers endow the spine with a natural flexibility and are preconstraint in a way, such that the equilibrium point lies in a vertical straight position. 8 cables with actuators play the role of tendons between the clavicle and pelvis to move the entire spine (See [15]). While these spines are in many ways the best example of such design, they require too many actuators and would not fit the small body of the *Robota* robot.

There exist also other hyper redundant robots, albeit not humanoids, such as the robotic elephant's trunk of the Clemson University [17] or various snake like robots (for example [18], [19]), which offer interesting solutions. The elephant's trunk of the Clemson University is composed of disks linked to one another by 2-DOF joints. These disks are used to drive the cable system which actuates the trunk. Between two disks, there are four preconstraint springs to create an equilibrium point when then trunk is in a straight position. The snake like robots cited above are driven by pneumatic pumps. The Slime Robot [18] is constituted of disks actuated by three pneumatic actuator between each of them. The OmniTread robot [19] is composed of different segments, each of them actioned by caterpillars. Between two segments, there is a pneumatic 2 DOFs joint. These robots offer interesting solution, especially in their actuation system. However, these robots have a structure which is meant to support a low load horizontally, and, thus, is not optimized to work under high compression,

Fig. 2. A demonstrator is teaching a movement which requires bending of the torso to the humanoid robot HOAP-2

as it is the case for the spine of a two legs standing-up humanoid robot.

III. Mechanical Design

The Robota project is concerned with the design and construction of a series of multiple degrees of freedom (DOF) doll-shaped humanoid robots, whose physical features resemble those of a human baby. The Robota project is part of a current trend of robotics research that emphasizes the need for the robot to bear some human likeness both in its body features and in the kinematics of its motions to enhance human-robot interactions, see, e.g. [20], [21], [22], [23].

As mentioned in the introduction, the use of the robot Robota as part of studies with children with autism [3] sets a number of constraints on its design, including that its size remain small, its weight light, its cost low and that its features remain aesthetic and familiar (similar to that of other toys the children would encounter in their daily life).

In order to ensure the overall aesthetic of the robot *Robota*, we took as reference the average size of a 60 cm tall commercial doll, see Figure 3 and a maximal weight of 4kg. These constraints were used for all precedent prototypes designed for Robota: The 7 DOFs arm, the 3 DOFs eyes and the 3 DOFs neck [8], [24]. Given the existing prototypes, the following constraints were given for the design of the spine:

1) The spine must be strong enough to support a load of 2Kg located at 80mm up the last vertebrae (see Fig. 12).
2) The spine must small enough to fit in a cylinder of 210mm high and diameter of 120mm.
3) The weight must not exceed 1.2kg.
4) The actuation must be done by a maximum of three motors, to remain cheap and easily controllable by an on-board controller (a PocketPC).
5) The spine must be able to bend with an angle of 40° in each direction.

While there exists a few prototypes of spines for humanoid robots, see [15], [16] and the introduction for a review, none of these suited the constraints listed above. The spine of the KENTA robot is too big and has too many actuators. The solution used for CLA is more relevant

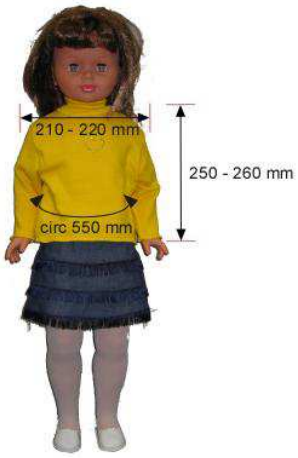

Fig. 3. Doll used as reference for setting the size of the new robot Robota.

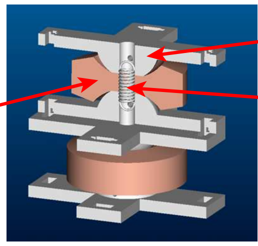

Fig. 4. A rubber disk is placed between each vertebrae and a spring is used to fix one vertebrae to another

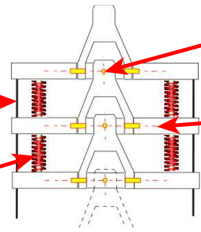

Fig. 5. The link between two vertebrae is a cardan joint and compression springs are placed on each branch to insure the stability

to our problem. However, it still has too many actuators for our purpose and it would not be suitable to carry the load (2Kg) of the robot's head and would lead to buckling problems. Ensuring that all components remain small (to fit within the doll's body) while supporting an important load (in proportion to the overall size of each limb) is and has always been a tremendous challenge in all the realizations we have developed.

A. *The first design*

To keep the control of the robot simple, we decided to decouple the three DOFs of the spine. Two DOFs are used to bend the spine from front to back and from left to right respectively, see Figure 11. The third DOF of the torso, supported by the spine, drives the horizontal rotation of the shoulders. A classical solution is used for the rotation of the third DOF. The point was to find a feasible solution for the two first DOFs. Different solutions have been explored during the project using different types of transmission means for the movement.

1) Cable system: The first design of the spine consisted in a stack of vertebrae separated by rigid polymer rings. The rings introduced a space between the vertebrae and limited the lateral displacements (see Fig 4). The vertebrae were fixed one to another by a spring passing through the rings. The shape of the rings allowed bending by maximum 30° between two vertebrae. There was a flat part between the rings and the vertebrae to allow a better stability in the rest position (straight vertical). Hole were drilled at each extremity of the cross formed by the vertebrae to fit the various cables needed for the electronic.

The first problem we encountered with this design was that the length of the spine would change when it bended, because the cables on both sides would not change by the same length (when the two cables are fixed along one axis, one winds up when the other winds out). The second problem was that, if we fixed the cables only to the upper vertebrae, the spine would bend each vertebrae separately and one after the other one, starting with the first one. Thus, the movement would not have been smoothly distributed along the spine.

2) Cardan Joint: To address the first problem mentioned above and inspired by the elephant's trunk solution [17], we replaced the polymer rings with a cardan joint with compression springs placed on each branch of the cross shape vertebrae near the cables (see Fig 5). The cardan joint solves the problem of the difference of displacement between antagonist cables.

However, this still leaved us with a control problem, when the cables are fixed only to the upper vertebrae. Here, the problem is not that the vertebrae will move one after the other (each joint act as directing axis and the springs distribute the forces across all vertebrae). When attaching a big load to the spine (here about 2kg), there will be some buckling problems, if the springs are not strong enough.

3) Screws instead of cables: To solve the buckling problem of the precedent solution, in a third design, the cables were replaced by screws and cardan joints (see Fig 6). At each level, we now find four screws instead of cables. The screws have different step depending on the level (small step at lower level and increasing for higher level). This creates a difference of displacement between two consecutive vertebrae. The different screws are linked with cardan joints. With this system, the displacement of each vertebra is under control.

The drawback, still, is that to achieve the desired bending of the spine, the step of the screw located at the last layer becomes very big and, thus, requires a larger interval between two vertebrae. Thus, the final prototype would end up being larger than originally planned.

4) Hydraulic systems: After the cables and screw transmission, we have decided to explore hydraulic solutions. The first design is presented in Fig 7. Each vertebrae is linked to the next one using a spherical bearing. This time again, each vertebrae consists of a cross shape. Each

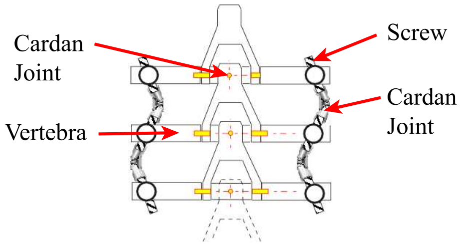

Fig. 6. The link between two vertebrae is a cardan joint and compression springs are placed on each branch to insure the stability

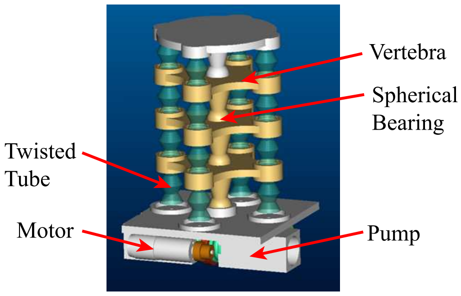

Fig. 7. The link between two vertebrae is a cardan joint and compression springs are placed on each branch to insure the stability

branch across two vertebrae is linked through a twisted tube. Between two tubes, the vertebrae is drilled to leave a way for the liquid. Thus each stack of tubes form a extensible column.

A hydraulic pump has been designed specifically for our purpose. The pump is located at the base of the spine. Two motors transmit the movement, via a set of reduction gears, to two parallel endless screws that moves two pistons inside tubes (see Fig 8). This creates a pump-in/pump-out traction system, similar to using a pair of syringes, (see Fig. 9).

Prototypes of twisted tube have been produced to test the resistance of such a system. The prototypes were tested under a pressure of 3 bar (the minimal pressure required to move a load of 2kg SeeIII). None of the tubes we have tested were sufficiently resistant to such pressure. The sensitive points are the fold of the accordion shaped tubes.

These problems have driven us to a more classical solution by using pistons instead of compressible tubes. The pistons are much more resistant to high pressure, but the problem is the difference of friction between the

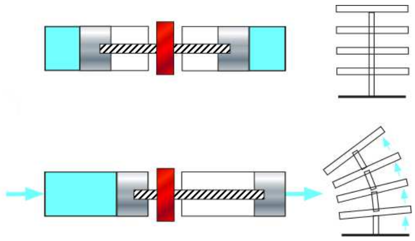

Fig. 9. Working principle of the hydraulic actuation of the spine.

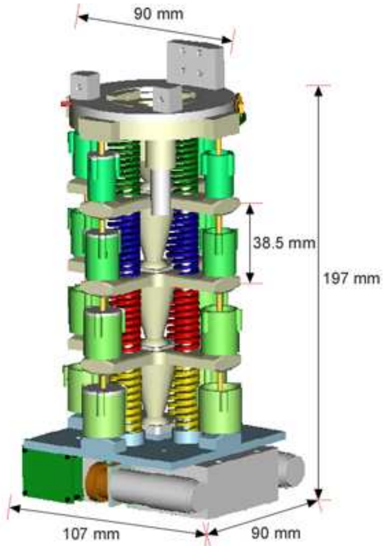

Fig. 10. Dimensions of the torso.

different pistons. We are unable to guarantee that all pistons will have the same comportment. That can result in the spinal cord forming an 'S' shape. To prevent this problem, we have placed four springs between each vertebrae.

B. Prototype of a 3 DOFs spinal cord

The current prototype of spine is about 200mm high for a diameter of 90mm. Its weight is about 1Kg and it can support a load of 2Kg located at 80mm on the spine (see Fig. 12). The hydraulic pump in located at its base (see description in III-A.4), and, thus, is not part of the supporting load. The complete spine is composed of four vertebrae, linked through spherical bearing. At each level

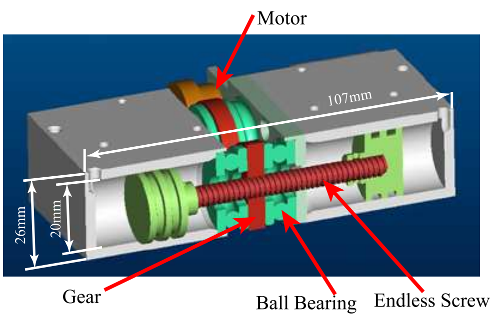

Fig. 8. Cut view of the traction system.

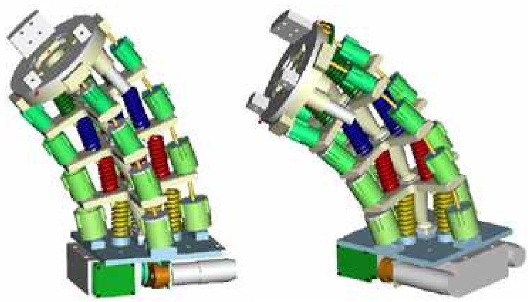

Fig. 11. Maximum bending of the spine

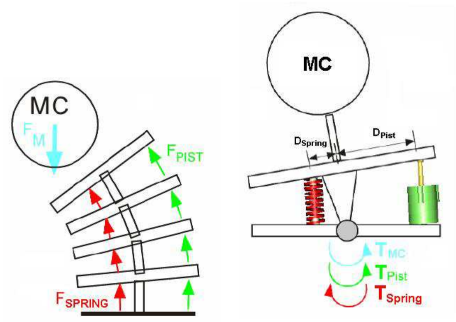

Fig. 12. Forces and torques acting on the system.

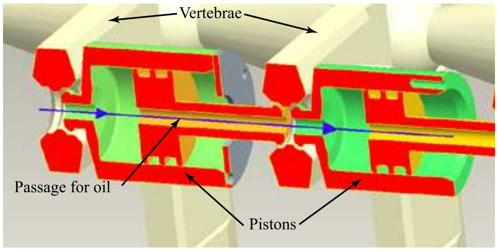

Fig. 13. The oil passes from one piston to another through the piston's axis.

have been placed four pistons and four springs, as described in III-A.4 and shown in Fig 10. The vertebrae and pistons are made of polymer and were mold in our laboratory.

Thus, for each DOF there are 2 columns of 4 pistons. Pure Olive oil is used to transmit the strength (as mineral oil would eat-up the polymer components). Inside each column, the oil passes from one piston to another trough the piston's axis (see Fig. 13). A rubber tube is used to provide etancheity between two pistons inside the vertebrae. Four flexible tubes are used to bring the oil in the four columns of the pistons. When moving a DOF, one set of pistons is expanding to give the necessary strength to bend the spine while the other stretch back without acting on the spine. The rubber tube used to bring the oil from one piston to another (through the vertebrae) prevents us from using the pistons in traction. Thus, the pistons work only in compression (see Fig 12). Because of the difference of torque acting on the base and the upper part when the spine is bending, the pistons diameters are bigger in the lower level. The diameter are respectively $25mm$, $22mm$, $19mm$ and $16mm$.

The additional springs added to each level increase the support forces and ensure that the spine would not bend nor rotate under the important weight of the upper body. In the same way than the pistons, the springs at the lower level are stronger in order to compensate for the difference in torque between higher and lower levels during bending. The springs constants K are from the lower to the upper level: $43.9N/mm$, $33.2N/mm$, $24.8N/mm$ and $16.4N/mm$

To control the bending of the spine, we have a 2 axial inclinometers placed in the upper vertebra and one in the base of the spine. A differential measurement of the

Fig. 14. Prototype of the traction system.

inclination gives the absolute position of the spine. These informations are given to the controllers of the two motors placed in the base. Thus we have a close loop control in position.

The third DOF is the rotation of the shoulder. This DOF is implemented on the last vertebra. A rotating tray is actuated by a motor and guided by a smooth bearing. Because we do not have any rotation axis, the rotation angle cannot be measured with a potentiometer. Here we use the motor's incremental encoder and two switches, placed at the end of the motor course, to detect the start and ending of the rotation.

Each motor is driven by its own motor module that allows PID control in position, speed and torque. Each module is accessible using a I2C bus and placed close to the motor it drives. Thus, the number of cables running through the robot is limited.

	Spinal Cord
Weight [gr]	1000
Size [mm]	200x90
Max Torque [nm]	3
Max Speed [Rad/s]	1.0
Motor control boards	3
Motors	2 Faulhaber 17mm 1 Faulhaber 10mm
Sensors	2 inclinometers 3 digital encoders 2 switches
Cost [$]	870

TABLE I

PRACTICAL DATA ON THE PROTOTYPE OF SPINAL CORD.

IV. TEST OF THE PROTOTYPE

We first tested the waterproofness of the pump. The pump system works perfectly without loss of oil. The double O'ring of the pistons prevent all possible loss.

Because of the novelty of the solution, we have, then, conducted incremental tests on the mechanical part during the building of all four levels of the spine. These tests have been done by using hand actuated interrupters to control the two motors of the pump.

To test the bending of the spine, we have built, first, only the first level: one vertebra with four pistons. Because we do not have any load the springs were not mounted. These tests have revealed sometimes a lack of waterproofness along the pistons, which had in the first version only one

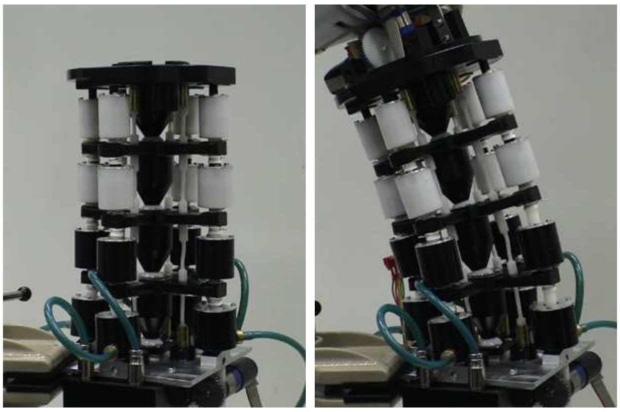

Fig. 15. Current prototype of Robota's spine.

O'ring. The problem was due to the fact that, if there is some loss, the pump is unable to re-inject oil in the system and the pressure cannot be guarantee. The pistons have been modified to have two O'rings each (see Fig 13) in order to prevent this problem.

Finally, the complete spine has been built (without springs to be tested unloaded), see Fig 15. This test has revealed two problems. First, it appeared that the tube used to transmit oil from one piston to another is too small, and does not allow enough pressure to fit the viscosity of the oil. The real viscosity of commercial (house-keeping) Olive oil was difficult to estimate beforehand, as it is not as well documented as that of classical mineral oil. Second, the double O'ring have each different friction factors. This difference was expected, (see III-A.4), but should have been negligible. Unfortunately, in combination with the first problem, this resulted in a blockage of the two last pistons (see the right picture of Fig 15). Currently, we are redesigning the transmission tubes and pistons to increase the pressure, while ensuring waterproofness.

V. DISCUSSION AND CONCLUSION

This paper presented the current prototype of spine for the robot Robota. The motivation behind the construction of Robota stems from the need to have a robot with realistic human features. Current commercially available mini humanoid robots do not have any spinal cord, they only have one or two degrees of freedom placed serially in the waist. We have developed a compact prototype of human-like spinal cord which is simple to control. This prototype can, however, be easily improved in many ways.

For instance, we chose to mold most of the construction using polymers to lower the complete cost of the prototype. It seems that the limit of this technology has been reached for this project. In the next version, we will probably have to build metallic pistons to ensure more precise diameters and, thus, to better control the friction and pressure along the piston. Metallic pistons will offer a greater resistance, which will allow one to have thiner walls for the cylinders and axes of the pistons.

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