Mechatronics of the Humanoid Robot ROMAN

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1 Introduction

Recent developments in the area of service robotics show an increasing interest in personal robots. Those personal robots can help to handle daily work and to entertain people. Both tasks require a robot that is able to communicate with people in a natural way. For these tasks non-verbal motions like gestures, mimic and body pose are more and more important. Several anthropomorphic robots like [1], [6], [8] and [7] have been build in recent years. Although several goals could be reached humanoid robots are not able to communicate with humans in a natural way.

Our concept of non-verbal interaction is mainly based on on FACS [4], which consequently describes the motions of the skin, eyes and neck. The results of FACS are extended with information concerning body pose and the influence on man-machine communication [5]. Based on these research results we present the mechanical design and construction of upper body, eyes and neck for the humanoid robot ROMAN. The mechanical design is an extension of the previously build emotional humanoid head with 3DOF neck construction ([3], [2]). Several experiments with the previously build head revealed the importance of additional expressive motions to realize a more natural man-machine communication.

2 The Humanoid Robot ROMAN

The mechanical design of the humanoid robot is adapted to Ekmans [4] and Givens [5] work. The possibility to express emotions is therefore mainly based on the availability of the so called action units which have to be combined to express a specific emotional state. Table 1 lists those action units which are very important and can be realized with the humanoid robot ROMAN. These motions include the movements of the artificial skin, the neck and the eyes. The movements of the upper body are not listed as action units so we decided to realize them similar to the natural human upper body motions. Figure 1(a) shows an image of the engineering construction of the humanoid robot while the silicon skin can be seen in Fig. 1(b).

Table 1. List of all realized action units corresponding to Ekmans numbering system including the approximated maximum ranges of motion

Skin Motions		Head Motions		Eye Motions	
1 Inner Brow Raise	$1cm$	51 Turn Left	60°	61 Eyes Left	30°
2 Outer Brow Raise	$1cm$	52 Turn Right	60°	62 Eyes Right	30°
9 Nose Wrinkle	$1cm$	53 Head Up	20°	63 Eyes Up	40°
12 Lip Corner Puller	$1cm$	54 Head Down	20°	64 Eyes Down	40°
15 Lip Corner Depressor	$1cm$	55 Tilt Left	30°	65 Walleye	30°
20 Lip Stretch	$1cm$	56 Tilt Right	30°	66 Crosseye	30°
24 Lip Presser	$1cm$	57 Forward	$2cm$		
26 Yaw Drop	10°	58 Back	$2cm$		

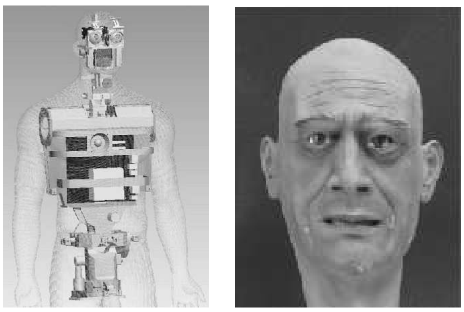

Fig. 1. *(a)* Engineering drawing of the upper body, the neck and the head construction included in Zygote's 3D realistic human model *(b)* A previous version of the humanoid robot "ROMAN" (ROMAN = RObot huMan inter-Action machiNe) with human-like silicon skin

3 Design Concept and Construction

Based on the insights of the previous chapter we present the mechanical design of upper body, the artificial eyes, the neck and the interior frame of the robot.

3.1 Upper Body

The movements of the human spine will be approximated with three degrees of freedom in relation to the base in an open kinematic chain. The kinematic scheme of the lumbar spine is similar to the one used in the design of the neck, while ranges of motion should be appropriate to the functions of the spine. The ranges of motion include rotation over vertical axis ($\pm 60°$), inclination forward/backward in relation to horizontal axis ($-30° and + 40°$) and inclination left/right in frontal plane ($\pm 30°$). Figure 2(a) shows the engineering drawing of the upper body.

It was assumed that two main boards will be located on the chest in the front and in the back side. For the synthesis and recognition of speech a four channel sound card and a loud-speaker in the front of the body will be applied. For the protection of the equipment the chest has to be adequately stable and safe, so the basic design of the chest has the form of a stiff box with artificial ribs for protection. The chest as a mechanical part should be adequately resistant to transfer gravitational and external moments/forces acting to the head and to upper limbs (arms, hands), and should be relatively lightweight. It was decided to use the typical shell-shaped design for the box with planar walls made as a bent of tick plates and welded duraluminium.

The mechanism (see Fig. 2(a)) consists of the base, rotational fork 1 driven by electric motor with gear, special cross yoke bearing by ball bearing in the fork 1 for inclination forward-backward and fork 2 for inclination left-right side bearing by ball bearing in the cross yoke. Driving forces (torques) are generated by electric motors with gears chosen in such a way, that typical compact solution of the motor with planetary gear is mounted to the fork (1, 2) and each one propels by small toothed wheel the big one mounted to the cross yoke. The total mass of the upper body including arms and head is estimated with up to $50kg$. To partially compensate the external torque over horizontal axes produced by gravitational forces, in the proposed solution it has been applied special additional bridges attached outside the cross yoke on each inclination axis with elastic elements for compensating changes of potential energy, i.e. external springs which can be seen in in Fig. 2(a).

Motor Dimensioning

$$M_{ext}(\alpha) = m \cdot g \cdot R \cdot sin(\alpha) \quad (1)$$
$$F_{spring_1}(\alpha) = 2 \cdot k_1 \cdot (l_1(\alpha) - l_{1_{min}}) \quad (2)$$
$$M_{spring_1} = -F_{spring_1} \cdot d_1(\alpha) \quad (3)$$
$$M_{spring} = M_{spring_1} + M_{spring_2} \quad (4)$$
$$M_{result} = M_{ext} + M_{spring} \quad (5)$$

The dimensioning to the motors is mainly dependent on the necessary torque. Figure 3(a) shows a sketch of the forward-backward bending joint which will be used to calculate the necessary motor torque. The static external torque $M_{ext}(\alpha)$ (see Eq. 1) is dependent on the mass of the humanoid robot. We assume an overall mass $m = 50kg$ (including the upper body construction with about $15kg$) at a distance $R = 0.4m$ with a gravitational acceleration $g = 9.81\frac{m}{s^2}$. The force created by the backside springs is dependent on the spring constants $k_1 = 1637.9$ and $l_{1_{min}} = 0.113m$ as well as the current length of the spring $l_1(\alpha)$ (see Eq. 2). The length $l_1(\alpha)$ can easily be calculated with the help of geometry. The force $F_{spring_1}(\alpha)$ is multiplied with two since two identical springs are mounted on each side. Equation 3 shows the generated torque which

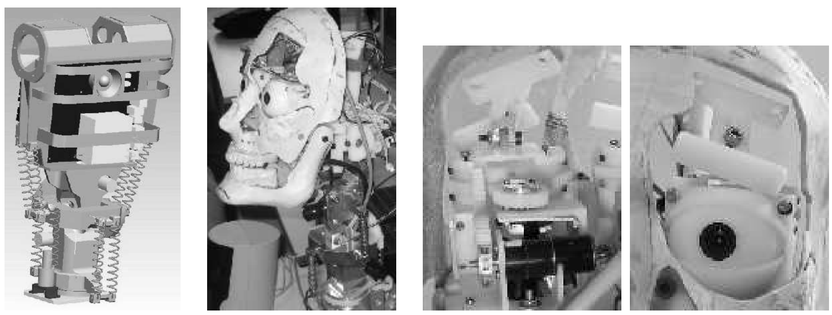

Fig. 2. *(a)* Engineering drawing of the upper body of the humanoid robot with integrated main boards, loudspeaker and the 3DOF hip with supporting springs *(b)* This image shows the assembled head and neck including the fourth neck joint *(c)* Mounted eye construction from the backside and *(d)* the frontal view with artificial skeleton

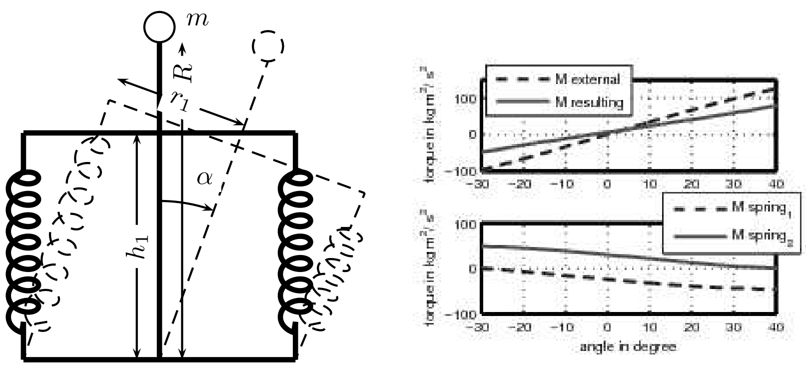

Fig. 3. *(a)* This sketch of the forward-backward bending motion is used to calculate the external and resulting torque in the rotational center *(b)* The upper diagram shows the external $M_{external}$ and the resulting torque M_{result} and the lower diagram shows the torque generated by the backside (M_{spring_1}) and front side springs (M_{spring_2})

is only dependent on the generated force and the orthogonal distance $d_1(\alpha)$ to the rotational center. Since the construction is not symmetrical a second torque generated by the springs on the front side of the construction has to be calculated in a similar way. The spring-generated torque M_{spring} (see Eq. 4) can than be used to calculate the resulting torque M_{result} as shown in Eq. 5. The maximum external torque of $126.11 \frac{kg \cdot m^2}{s^2}$ could be reduced with the help of the springs to $79.44 \frac{kg \cdot m^2}{s^2}$. Figure 3(b) shows the previous and the resulting torque as well as the spring-generated torques dependent on the angle α. From the analysis it is shown, that the driving system (motor with planetary gear and one step wheel gear) should generate about $60 - 65\%$ of the maximum value of external gravitational torque.

3.2 Artificial Eyes

The construction of the eyes must be compact and lightweight since space is limited and we must be able to move the eyeballs independently up/down and left/right. The upper eyelid has to be movable to assist the expression of emotions. Additionally a small camera has to be integrated in the eyeball which is connected to exterior electronic parts with a flexible cable.

The eyeball shown in Fig. 2(c) slides in a spherical attachment and can be moved with 2 pins in the rear part of the eye. Each pin is directly connected to a gearwheel and a stepper motor to allow a high the positioning accuracy. The third gearwheel is used to move the upper eyelid. In comparison to the human eyeball which has a diameter of $23mm$ to $29mm$ the eyeball of the robot has a diameter of $46mm$. We increased the dimension to include the lightweight camera ($12g$) and get an iris with a diameter of $16mm$ which is necessary for the camera. The complete construction of a single eye has a weight of $150g$ including the motors and gears. The eyeball alone has a weight of $38g$ and can be moved with a maximum torque of $126mNm$ (vertical axis) and $136mNm$ (horizontal axis). The eyes are able to move $\pm 40°$ in horizontal and $\pm 30°$ in vertical direction and can be moved from left to right or top to bottom in about $0.5s$. The eyelid can be moved $70°$ up- and $10°$ downwards from the initial horizontal position while a blink of an eye can be realized in $0.4s$.

3.3 Neck

The formerly 3DOF design of the neck must be extended to a 4DOF design to realize motions like nodding which is important for non-verbal communication. The axis of the fourth joint is located next to the center of the head to realize a rotation along the heads pitch-axis. The connection between neck and fourth joint is build of aluminum which has an increased stiffness in contrast to POM (Polyoxymethylene). The design of this connection is shifted to the rear of the head to form some free space which is necessary for head rotation. The rotation is assisted by two springs with a maximum force of $27N$ each since the center of gravity is placed in the front part of the head. The motor is able to generate a torque of $1230mNm$ to move the head with all actuators and sensors. Figure 2(b) shows the construction of the fourth neck joint including gearwheel and motor. Additional information concerning the neck can be found in [2].

4 Robot control architecture

The actuator system of the robot consists of 21 different motors including seven dc-, six stepper- and eleven servo-motors.They are connected to the digital signal processor unit (circuit board) which consists of a DSP (Freescale 56F803) cooperating with a logic device (CPLD - Altera EPM70256). Additionally there are current supply elements, CAN-bus elements and amplifiers for the motors. This digital signal processing unit is able to preprocess different types of encoders and controlling up to two dc motors, three stepper motors (via a TMC428 stepper motor controller) and six servo motors. Several DSP units are connected via CAN-bus to an embedded PC which is placed inside the robot case.

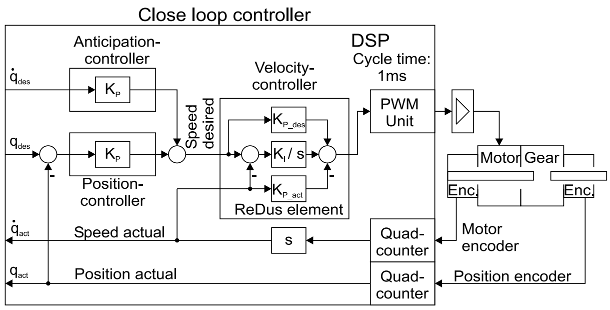

Fig. 4. The controller structure for one joint

The controller for dc-motor has been implemented as presented in Figure 4. The controller itself consists of a cascaded closed loop velocity controller and a closed loop position controller. The velocity controller is an advanced PI-Controller, where the proportional value for desired and actual inputs are separated. This type is called ReDus unit and has the advantage, that only via the proportional element frictions of the motors can be compensated and the desired input can be reached without having a difference to the actual input. The integral element is only responsible to compensate external forces to the joint. This concept makes the controller quicker and more stable. The superposed position controller is combined with an anticipation element. The known velocity of the position calculation is an direct input to the speed controller. Differences in the position must be compensated by the position controller. No difference between the position actual and desired input must be build up to get a higher desired speed. The drag distance between desired and actual position value is shorter. This type of controller supports different mounted positions of the velocity and position sensor. Certainly this works only, if the desired values from the topper modules are correct and are available continuously.

The robot control on the personal computer is implemented with the help of the Modular Controller Architecture (MCA). MCA is a modular, network transparent and real-time capable C/C++ framework for controlling robots. MCA is conceptually based on modules, groups and edges between them, which allow the implementation of hierarchical structures. The tools mcagui and mcabrowser allow the interaction with the system allowing the user to control and observe the robot.

5 Conclusion and Outlook

Based on psychological research results concerning the interaction between humans we designed an emotional expressive humanoid robot. Equipped with 24 degrees of freedom and a complex sensor system the mechanical design allows complex interactions with humans in a natural way.

It is also obvious that the integration of human-like arms will have a great influence on the communication task, so these will be added in near future. Based on this mechanical design it is necessary to extend the current behavior-based controlling architecture to realize first natural dialogs.

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