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# Cost Oriented Control of Humanoid Robots

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**Abstract:** As humanoid robots assume more important roles in applicable areas, they are expected to operate in the environment for human, to adapt to unknown environment and to replace humans in hazardous operations. There is a large number of publications which closely elaborate and scrutinize issues regarding the control of humanoid robots available but only few are based on modern control theories. Furthermore, according to the new headline "Cost Oriented Humanoid Robots – COHR" the new control concept has to fulfil in addition other features. Therefore, main purpose of this paper is to develop control system for humanoid robots that are cheaper than the current state-of-the-art. The new control concept will be implemented and tested on the real COHR robot (ARCHIE) available at the IHRT (Intelligent Handling and Robotics).



Keywords: humanoid robots, control, walking, cost oriented

## 1. INTRODUCTION

Future needs for the robots have started to change from classical automation to robotic systems that are friendly for humans. Knowing that our cities, roads, homes and businesses are built for human beings (bipeds), in fact, society has designed everything that suits for human shape, this becomes a very important matter to be taken into account when talking about the future of robotics. (Shuuji Kajita, 2014)

Nowadays, one of the most concerning issue in the field of humanoid robots is the high cost. Many schools, colleges, and laboratories may not be able to invest much in this field of research. Also another problem is that most of the people do not have sufficient skills and knowledge to understand the complexity of design of hardware and software that is used in the development of humanoid robot platforms. Therefore, there is a keen interest to develop humanoid robots that are low cost, simple construction and which bear the ability to learn and have a higher level of autonomy (decision-making). (Rodrigo Nuno Mendes Antunes, 2015)

Indeed to fill these gaps and meet the required needs there has been built "Archie" robot by the Institute of Intelligent Handling and Robotics (IHRT) at the Technical University of Vienna which is cost oriented and this robot has a duty to support and assist people in everyday affairs. Currently, the robot consists of 18 degrees of freedom and is able to perform basic human-like walking motion. (Kopacek, 2011)

One of the most important and complex system of humanoid robots is the control system, because of higher degree of freedom and non-linear behaviour of joints. This means that when designing a control system of humanoid robot these constraints should be taken into consideration. For humanoid robots, the main problem while walking is the balance and so far the solutions are not satisfactory for applications in the real world. Therefore, all control systems of a humanoid robot are designed to maintain the robot's balance and give the robot the ability to walk.

In most of the publications in the field of humanoid robots the cost of the robot is not taken into consideration, especially the cost of the control system has not been examined.

Generally, robots are using PID controllers, also in humanoid robots the PID controllers are widely used. The main difference between these PID controllers is that in humanoid robots the PID coefficients are adjusted to be adaptive. In some works these coefficients are calculated by using fuzzy logic, genetic algorithms and various methods of optimal control

Most of the humanoid robots are based on hierarchical distributed control systems. In this type of control, the system (robot) is organized and divided into local parts controlled using 10 individual controllers. All of the individual controllers are communicated with the main controller to unify their functionality in order to reach a certain purpose for the whole robot. (Byagowi, 2010)

## 2 JOINTS CONTROL

The Archie robot mainly operates by using two types of motors, brushless DC motor (BLDC) and DC motor. In Archie's knee, ankle and hip are used Brushless DC motors (i.e Maxon-Motors, EC45) 24V, because of their high efficiency and the low noise, see figure 1. To control the robot's joints in Archi the Elmo Motor controllers are used, which are industrial controllers. It is comprised of PI


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cascaded controller and power amplifier. This compact drive enables the user to select the three different modes of controlled output: position, velocity and current modes. Then automatic or manual tuning of controller gain is done according to the operating situation using the Composer software. The nominal voltage needed for the electric drive is 50 $V$ and its output power is 480 W. The disadvantage of using the Elmo controller is its high cost and this is contrary to Archie's development goal.

Fig. 1 Brushless DC motor

As it is mentioned above, the main objective of the development of the Archie robot is cost orientation, but the control system is in contradiction with these objectives. One of the systems that increase the cost of a robot is the control system. In this paper, Elmo controllers will be replaced with a low cost controller. So the main goal is to replace the current control system, where one of the main parts of control system is the Elmo controllers. Elmo controllers will be replaced with a BLDC drive and an Atmel (ATmega328P) microcontroller. The price for controlling a robot's joint with the Elmo controller costs 500 €, while the new system costs from 15 to 18 € but the performance of the new control system will be same.


Fig. 2. Brushless DC motor (BLDC) driver

The new control system consists of a BLDC motor with hall sensor, also with an angle sensor which is located at the output of the motor shaft, Atmel (ATmega328P) microcontroller, BLDC drive and power supply. Microcontroller detects signals from motor shaft and calculates the position of the angle and compares it to the desired angle position. Since the BLDC motors used in the Archie robot are 24 V and the microcontroller outputs are 5 V, so in this case BLDC motor drivers are used, see figure 2.

By reading the sensor data, the microcontroller generates a PWM signal. The drive is supplied with a voltage of 24 V and it controls the BLDC motor speed by using the PWM signal generated by microcontroller. The driver controls the gates of the MOSFET, so the voltage supply (Vcc) can be passed to the BLDC. The voltage and current passing through the MOSFET, in coordination with the logic circuit controlled by the microcontroller, sends voltage to the motor windings in order to rotate the shaft of the motor.

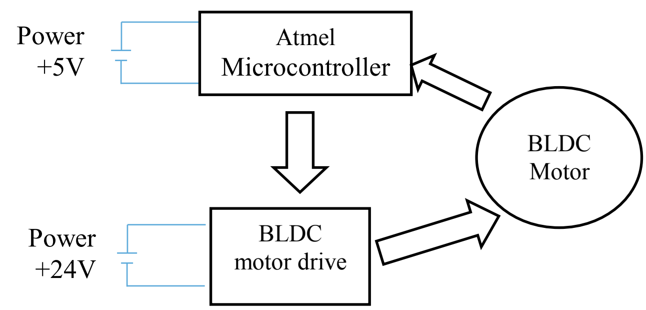


Fig. 3. Control scheme for one joints

In order to define the position of the motor shaft the angle sensor (AS 5134) is used. AS5134 encoder is a magnet without contact for measuring the correct angle during rotation of the shaft for 360°. To measure the rotation angle, the two pole magnet is required to be rotated around the chip. Angle measurement provides instant information about the magnitude of angle position with an 8.5-bit resolution per 360° rotation. In addition to the angle information, the magnetic field strength is also available as a 6-bit code.

In our case the angle sensor is mounted at the output of the harmonic gearbox and the permanent magnet is connected to the motor shaft.

Since the motor shaft and output of the harmonic driver rotations are in the opposite direction, this configuration will cause a displacement in the position of the magnet after each harmonic driver output rotation. During rotation of the motor shaft in a certain direction, the output of the harmonic driver will be in the opposite direction with a degree of reduction. The harmonic driver's rotational speed reduction rate is 160.
Regarding the described mechanism of placing the encoder on the output and sensing the position of the magnet coupled to the rotor of the brushless motor, there is 362.25° degrees per revolution. (Byagowi, 2010)

$$\theta = 360^{\circ} + \frac{360^{\circ}}{160} = 362.5^{\circ} \tag{1}$$

Each joint uses an independent controller which controls torque, velocity and position using the PI (proportional and integral control) loops. Feedback for each joint is provided by angle sensor.

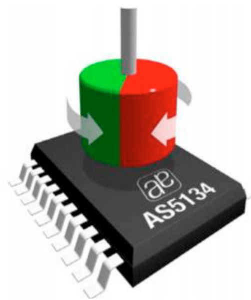


Fig. 4 Angle sensor (Austrian Microelectronics, 2019)

## 3 MODEL OF THE JOINT PLANT

In this part will be built the mathematical model of the three phase BLDC motor. In most applications of BLDC motors, the stator windings are Y-connected in which neutral point is not used so in this case the phase detection is difficult. So the mathematical model based on the phase voltage will not be applied in this work, but will be applied line-line voltage because it is much easier to measure the voltage.

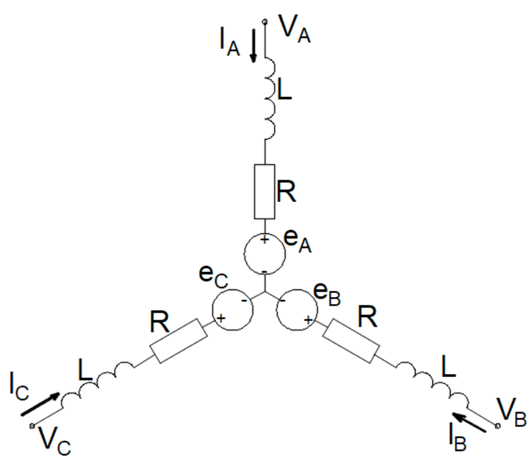


Fig.5 The equivalent circuit of brushless DC motor

Line to line voltage lines are expressed in matrix form (fig.5):

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} + \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} + \begin{bmatrix} e_A-e_B \\ e_B-e_C \\ e_C-e_A \end{bmatrix} \quad (2)$$

Where $V_{AB}$, $V_{BC}$ and $V_{CA}$ are the phase voltages, $I_A$, $I_B$ and $I_C$ are the phase currents, $e_A$, $e_B$ and $e_C$ are the back emfs, M is the mutual inductance, R is the stator resistance per phase and L is the inductance. (Oguntoyinbo, 2009)

The equation of line voltage A-B:

$$V_{AB} = V_d = 2RI + 2(L-M)\frac{dI}{dt} + 2e_A = R_a I + L_a \frac{dI}{dt} + k_e \omega \quad (3)$$

Where:

$R_a$-line resistance of winding, $R_a = 2R$

$L_a$-equivalent line inductance of winding, $L_a = 2(L-M)$

$k_e$ –the back emf coefficient

M – mutual inductance

From the second law of Newton, the equations of motion for the mechanical part of the motor as follows (fig.6):

$$J\ddot{\theta} + b\omega = T_e - T_L \quad (4)$$

J –the rotor inertia

b –viscous friction coefficient

ω –Angular velocity

$T_e$ – electrical torque

$T_L$ – load torque

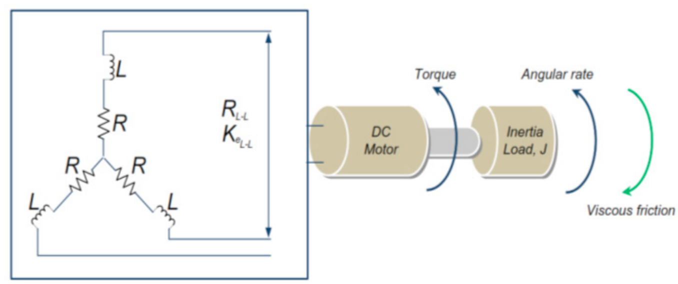


Fig. 6. Brushless DC motor scheme (Oguntoyinbo, 2009)

Electrical torque is:

$$T_e = K_T I \quad (5)$$

Substitute (5) in (4),

$$J\ddot{\theta} + b\omega = K_T I - T_L \quad (6)$$

Assume torque load $T_L$=0

$$I = \frac{J}{K_T}\frac{d\omega}{dt} + \frac{b}{K_T}\omega \quad (7)$$

Substitute (7) in (3),

$$V_d = L_a \frac{J}{K_T}\frac{d^2\omega}{dt^2} + \frac{R_a J + L_a b}{K_T}\frac{d\omega}{dt} + \frac{J}{K_T}\frac{d\omega}{dt} + \frac{R_a b + k_e K_T}{K_T}\omega \quad (8)$$

Using Laplace transform,

$$G(s) = \frac{\omega(s)}{V_d(s)} = \frac{K_T}{L_a J s^2 + (R_a J + L_a b)s + (R_a b + k_e K_T)} \quad (9)$$

So by re-arrangement the transfer function as ratio between angular velocity and source voltage, is:

$$G(s) = \frac{\omega(s)}{V_d(s)} = \frac{K_T}{R_a b + k_e K_T}\frac{\omega_n}{(s^2 + 2\xi\omega_n s + \omega_n^2)} \quad (10)$$

Where:

$\omega_n = \sqrt{\frac{R_a b + k_e K_T}{L_a J}}$ - natural frequency of the second-order system

$\xi = \frac{1}{2}\frac{R_a J + L_a b}{\sqrt{L_a J(\mathrm{R}_a \mathrm{b} + \mathrm{k}_e \mathrm{K}_T)}}$ -damping ratio of the second order system

$K_T$ – torque constant

So by re-arrangement of equation (10), the transfer function will be:

$$G(s) = \frac{\theta(s)}{V_d(s)} = \frac{K_T}{R_a b + k_e K_T}\frac{1}{s\left(s^2\tau_m\tau_e + s\tau_m + 1\right)} \tag{11}$$

Where, mechanical time constant is:

$$\tau_m = \frac{R_a J + L_a b}{R_a b + k_e K_T} \tag{12}$$

The electrical time constant is,

$$\tau_e = \frac{L_a J}{R_a J + L_a b} \tag{13}$$

Considering the following assumptions, the viscous friction coefficient value is very small, so b tends to zero, this implies that:

$$R_a J \gg bL_a$$

$$k_e K_T \gg R_a b$$

The transfer function finally for angle as output is written as:

$$G(s) = \frac{\theta(s)}{V_d(s)} = \frac{1/k_e}{s\left(s^2\tau_m\tau_e + s\tau_m + 1\right)} \tag{14}$$

By applying the assumptions in mechanical time constant and electrical time constant, we will have:

Where, mechanical time constant is:

$$\tau_m = \frac{R_a J}{k_e K_T} \tag{15}$$

The electrical time constant is,

$$\tau_e = \frac{L_a}{R_a} \tag{16}$$

Also after the replacement and re-arrangement, natural frequency and damping ratio will be:

$$\omega_n = \sqrt{\frac{k_e K_T}{L_a J}} = \frac{1}{\sqrt{\tau_m \tau_e}} \tag{17}$$

$$\xi = \frac{1}{2}\tau_m\omega_n = \frac{1}{2}\sqrt{\frac{\tau_m}{\tau_e}} \tag{18}$$

## 4. CONCLUSIONS

One of the main challenges in the development of humanoid robots is the complexity of design and the price. Their price has restricted their use. One of the most important and high cost systems in humanoid robots is the control system.

In the current Archie control system, an Elmo controller is used. This controller is very good in performance but its price is very high, which is contrary to the Archi robot's objectives and developments. Elmo controllers are replaced with a BLDC drive and an Atmel microcontroller. The price for controlling a robot's joint with the Elmo controller costs 500 €, while the new system costs from 15 to 18 € but the performance of the new control system will be the same.

One of the major challenges in reducing Archie's cost is Harmonic Driver's price, which costs over 1000 euros.

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