Development of a Low-Cost Humanoid Robot: Components and Technological Solutions

Vítor M. F. Santos, Filipe M. T. Silva

[1]University of Aveiro, DEM, TEMA, Portugal, vsantos@mec.ua.pt
[2]University of Aveiro, DET, IEETA, Portugal, fsilva@det.ua.pt

Abstract

The paper presents a set of solutions to build a humanoid robot at reduced costs using off-the-shelf technology, but still aiming at a fully autonomous platform for research. The main scope of this project is to have a working prototype capable of participating in the ROBOCUP humanoid league, and to offer opportunities for under and pos-graduate students to apply engineering methods and techniques in such an ambitious and overwhelming endeavor. The most relevant achievements on this implementation include the distributed control architecture, based on a CAN network, and the modularity at the system level. These features allow for localized control capabilities, based both on global and local feedback from several sensors, ranging from joint position monitoring to force sensors. Force sensors on the feet were designed and integrated using strain gauges properly calibrated and electrically conditioned. Although some issues are yet to be completed, the stage of development is already enough for practical experiments and to obtain positive conclusions about the solutions proposed.

Keywords: Humanoid robot; Biped locomotion, Distributed control; Force sensors

1 Introduction

In recent years, there has been a large effort in the development of humanoid robot prototypes and in the control and analysis of biped gaits. Research in bipedal walking can be divided into two categories: passive mechanisms and active walkers. The passive mechanisms are interesting because of their simplicity, energetic efficiency and consistency of the resulting gaits, but only in a limited range of operational conditions [1][2].

In the other extreme of the spectrum are the active walkers, falling largely into two groups: time-dependent and time-invariant. By far, the most popular are time-dependent that involve the tracking of pre-computed trajectories [3][4][5]. One of the most prominent schemes used to enhance trajectory tracking controllers or to analyse their stability is the so-called Zero Moment Point criterion [6]. In addition to the various time-dependent algorithms, there have been several other time-invariant control schemes proposed [7][8]. The results obtained with time-invariant schemes are impressive by inducing dynamic walking, but it is unclear how stability is achieved and how robustness or efficiency can be improved.

The paper presents the design considerations of a small-size humanoid robot under development. The main scope of the project beneath this paper has been the development of a humanoid platform to carry out research on control, navigation and perception, and to offer opportunities for under and pos-graduate students to apply engineering methods and techniques. Purchasing a commercial platform carries prohibitive costs and it would reduce the involvement at the lowest levels of machine design, which was posed as a relevant pursuit for the desired engineering approach. Moreover, recent advances in computing hardware have promoted research of low-cost and easy-to-design humanoids [9][10].

In this line of thought, the project aimed at building a prototype capable of participating in the ROBOCUP humanoid league. A wide range of technologies need to be integrated and evaluated, giving added value for project-oriented education. The design and development of the autonomous humanoid platform has considered three phases:

- Definition of functional and physical requirements, *i.e.*, mechanical structure, dimensions and degrees of freedom (DOFs);
- Selection and integration of hardware and software to achieve these requirements;
- Development of low and intermediate level tasks (*i.e.*, hardware and sensor oriented).

In what concerns the physical and functional requirements, the initial considerations were largely imposed by the rules of the ROBOCUP, namely, the robot dimensions, the mobility skills, the high level of autonomous operation and the selected tasks (e.g., walk, turn, kick a ball). As consequence, many technologies need to be integrated and a number of technical breakthroughs must be accomplished. The demands for limited costs gave rise to the selection of off-the-shelf materials and components.

One major concern of the project is to provide modularity at the system level. The main advantage is the possibility of reusing specific modules, in terms of both hardware and software, with no major efforts. A key concept for the control architecture is the distributed approach, in which independent and self-contained tasks may allow a standalone operation. At the same time, the increase of computational power may allow the development of more sophisticated sensor fusion schemes.

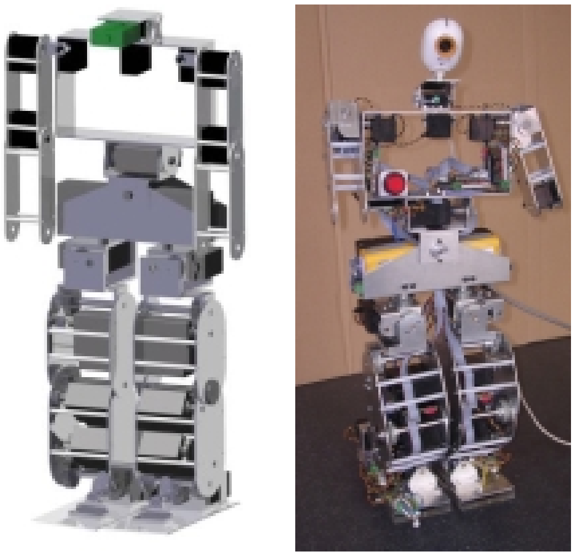
The design process has revealed much about the several problems, challenges and tradeoffs imposed by biped locomotion. As in most systems, the design options that are taken deeply influence the used technology, and vice-versa. Here, the emphasis is made on the mechanical design, the selection of actuators and batteries, the sensorial integration and the control system architecture. Though much work remains to be done in exploiting the potential of the proposed tools, the first results achieved at the present stage of the project are also presented.

2 Mechanical Structure for the Robot

When conceiving a robotic platform, namely a humanoid, countless decisions have to be made. Specifications and target applications must be defined and applied to impose limits both on skills and overall objectives.

After the structure height (ca. 60 cm) and remainder body proportions, the very first issue has been the number of degrees of freedom, namely to ensure proper and versatile locomotion. Walking concerns can range from simply ensuring robust equilibrium for static walking up to, hopefully, dynamic walking which will be a must for energetic efficiency.

The most versatile humanoids presented in ROBOCUP, and elsewhere, show up six DOFs per leg, namely one universal joint at the foot, a simple joint on the knee and a spherical joint on the hip, where, nonetheless, a simpler universal joint can still deal with many of the walking demands. Connecting the legs to the upper structure of the abdomen was decided to be done with two DOFs mainly aiming at greater flexibility in control to balance and account for the perturbations of the center of mass (CoM). So far, arms have been poorly defined and the head accounts for two DOFs for the future vision based perception. A complete humanoid model and a view of the current stage of implementation are illustrated in Fig. 1.



Degrees of freedom	
Head	2
Arms	3 (2×)
Trunk	2
Hip	3 (2×)
Knee	1 (2×)
Foot	2 (2×)
Total	**22**

Fig. 1. Model of the humanoid robot and the current stage of implementation

3 Motors and Batteries

For the dimensions involved, and for good autonomy, low cost off-the-shelf technologies for actuation do not offer significant alternatives other than the small servomotors, such as those from FUTABA, HITEC, and similar, used worldwide. To pick the adequate motors, several static (and some dynamic) simulations were carried out to estimate motor torques. The 3D structural model developed in CATIA furnished the CoM of the several links of this multi-body system, and were then fed into a pseudo-static model developed in Matlab, and calculated all motor torques along a sequence necessary to produce a locomotion step. Torques were obtained using $T_k = \left\| \sum_{i=k}^{N} m_i \mathbf{r}_i \times \mathbf{g} \right\|$, where $\mathbf{r}_i$ is the relative vector position of the CoM of link i, m_i is its mass and $\mathbf{g}$ the acceleration of gravity vector. The Matlab model was based on the superimposition of several open kinematics chains built using the Denavit-Hartenberg methodology. The simulation results shown in Table 1 indicate that the most demanding situations occur at the hip joint responsible for lateral opening of the legs, showing up torques on some joints greater than 2.5 Nm.

Table 1. Extreme angles and motor torques during one step in locomotion

Motor/Joint	$_1$ [º]	T_1 [N.m]	$_2$ [º]	T_2 [N.m]	$_3$ [º]	T_3 [N.m]
Foot 1 roll	0.0	2.37	7.1	0.98	7.1	0.95
Foot 1 tilt	4.7	0.30	10.1	0.20	10.1	0.17
Knee 1	10.1	0.76	21.8	1.17	21.8	0.80
Hip 1 tilt	5.4	0.35	11.7	0.30	11.7	0.07
Hip 1 roll	0.0	**2.26**	7.1	**2.57**	7.1	**2.54**
Foot 2 roll	0.0	0.00	7.1	0.00	7.1	0.00
Foot 2 tilt	4.7	0.12	10.1	0.12	38.0	0.12
Knee 2	10.1	0.17	21.8	0.23	52.9	0.29
Hip 2 tilt	5.4	0.07	11.7	0.02	15.0	0.35
Hip 2 roll	0.0	0.01	7.1	0.30	7.1	0.27

The HITEC servos (as FUTABA and their “clones”) occur in several variants of torques, dimensions and power. The models chosen for this system are described in Table 2.

Table 2. Selected HITEC Motor models for the robot

Application	Model	Mass (g)	Torque (Nm)
Arms and small torque joints	HS85BB	19.8	0.35
Legs and high torque joints	HS805BB	119	2.26

It is obvious from Table 1 and Table 2 that several joints require gear ratios greater than 1:1. That was done mainly for the leg joints, and gear ratios of 2.5 (and more) were used. This would give a theoretical maximal torque of 5.6 Nm, which accounts for overall efficiencies as low as 46%, thus giving some room for less efficient implementations. Early simple gear couplings were later replaced by toothed belt systems for improved transmission and tuning facility. Ball bearings and copper sleeves contribute to improve mechanical efficiency. Actuating with this servomotor has the disadvantage that velocity can not be automatically controlled. That is being overcome by an algorithm based on dynamic PWM tracking using the servo own potentiometer for feedback information. Velocity is now going to be controlled in slots of 10 ms, or less.

Power to drive the motors is a crucial issue since servos require a relatively high current, namely at startup and when producing motion in some configurations. Two ion-lithium batteries were installed and the system counts with a 7.2 V/9600 mAh pack, with maximal sustained current specified by the vendor at more than 19A. Each one of the two battery sets weights circa 176 g and confines to a box of 37x37x65 mm^3. Proper fusing, polarity protection and charge monitoring were also implemented.

4 Sensors

As all systems intended to be autonomous, this robot has both proprioceptive and exteroceptive sensors. For now, only the former exist and the following data is monitored: joint position, motor electric current, force sensors on both feet to measure ground reaction forces, accelerometers, used mainly as inclinometers (ADXL202E from Analog Devices), and a gyroscope for instant angular velocity measuring (GYROSTAR ENJ03JA from MURATA). Accelerometers and gyro are of the integrated type based on MEMS technology. Force sensing was custom made using strain gauges properly calibrated and electrically conditioned; a device with four strain gauges was arranged near the four corners of the foot base. The model and a prototype of the sensitive foot base are shown in Fig. 2.

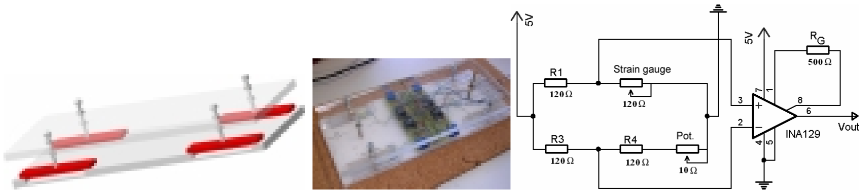


Fig. 2. Sensitive foot: model, device prototype, and electrical interface.

Current monitoring in the motors is made through a 0.47Ω power resistor in series with the motor power supply line, and an analog value is acquired by the local microcontroller. The hardware implementation can have other sensors, and a piggy-back electronic board has been left prepared for that.

5 Control System Architecture

One of the major challenges of the project was to conceive and implement a distributed control system. To allow for short and possibly longer term developments, the platform was given a network of controllers connected by a CAN bus in a master/multi-slave arrangement. The master unit performs no device low-level control, but dispatches orders and collects information to be exchanged with a central system that currently is still located on an external computer, but is expected to be implemented in a PC104-based board or similar.

Each slave controller can control up to three joints and consists of a PIC18F258 device (from Microchip) with its own program made up of local low-level actuator control. This possibility of local units with their own control ability allows for more elaborate strategies, since they can simply accept directives from upstream controllers or implement their own control decisions (or a combination of both). This ability releases the higher level control units from the burden of being aware of all details of control and perception (control laws, PWM generation, sensor processing, etc.). A simplified version of the control system is shown in Fig. 3.

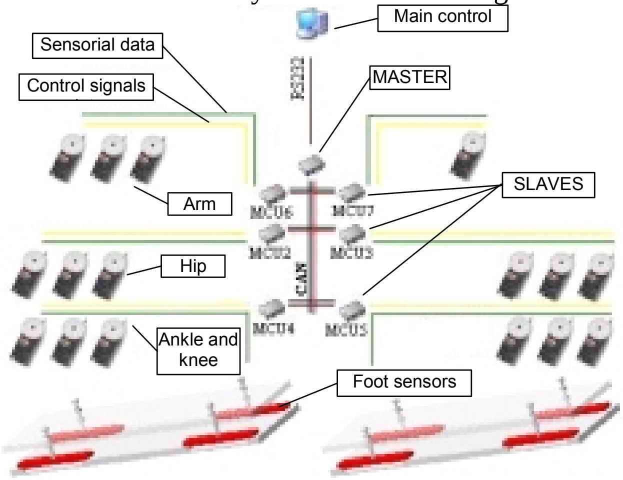


Fig. 3. Simplified Diagram of Robot Control Architecture

All communications are asynchronous and occur at two levels: among master and slaves on the CAN bus (1 Mbit/s) and between master and high level controller (currently serial RS232 at 38400 baud). Data exchanged between the master and each of the (currently) eight slaves refers to position and velocity set-points for motors and sensorial feedback from sensors associated to each slave controller. Each CAN message has 8 bytes, which allows control and perception refresh periods of circa 150 µs per slave, or a grand total 1.2 ms for 8 slaves, that is, a global network control cycle over 800 Hz. Of course, the serial link to upper controller does not need to be that fast since not all data and commands are expected to be exchanged throughout the entire control architecture. The upper control level will deal with vision and global motion directives, as well as any kind of planning and navigation to develop in the future. All this, however, is much slower than the microcontrollers which operate at 40 MHz and ensure a PWM resolution of about 1 µs, and sensorial acquisition rates at tenths or hundreds of kHz.

6 Conclusions and perspectives

This paper presented specific technological solutions and approaches to build a relatively low cost humanoid robot based on off-the-shelf components. The main features of this 22-DOF system include a distributed control architecture with local control possibility, based on a CAN network, and is prepared to use several types of sensors, ranging from joint position monitoring to force sensors on the feet made with standard low cost strain gauges. Most of the final platform hardware has been built and results are promising since the system now is able to stand, lean on the sides and forward-backward, and primitive locomotion steps have been achieved. Ongoing developments cover the inclusion of vision and its processing, possibly with a board based on PC104 (USB or IEEE1394 camera to be selected). Currently, what has been developed is only a platform for research; for the next few years, the research will cover distributed control, alternative control laws, like neural computation, and also deal with issues related to navigation of humanoids and, hopefully, cooperation.

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