Engineering Solutions to Build an Inexpensive Humanoid Robot Based on a Distributed Control Architecture

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Abstract - **Building a humanoid robot is a formidable engineering task requiring the combination of mechanical, electrical and software technologies. This paper presents the main steps to design a low cost fully autonomous humanoid platform and the set of solutions proposed. The main scope of the project beneath this paper is to carry out research on control, navigation and perception, whilst offering opportunities for under and pos-graduate students to apply engineering methods and techniques. The main features of the 22 degrees-of-freedom robot include the distributed control architecture, based on a CAN bus, and the modularity at the system level. Although some issues are yet to be addressed, the stage of development is already mature for practical experiments and to obtain the first conclusions on the potential of the proposed solutions.**

Index Terms - **Humanoid robots; Mechanical components and design; Modular architectures; Distributed control.**

I. INTRODUCTION

During the last few years, the number of research and development projects aimed at building humanoid robots has been increasing largely. The success of the Honda walking robots has attracted the attention of a wide audience even beyond the scientific community [1]. On one hand, humanoid robots developed behind industrial funded projects tend to have impressive walking abilities, while requiring dedicated components and expensive materials [2][3]. On the other hand, the continuous progress in robotics technology opens up new possibilities for academic research on low-cost and easy-to-design humanoids [4-6]. A significant effort has been made in control and gait analysis. [7-15].

The main scope of this project has been the development of a humanoid platform to carry out research on control, navigation and perception, and also to offer opportunities for under and pos-graduate students to apply engineering methods and techniques in such ambitious and overwhelming endeavour. 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. The ultimate goal of the project is to build a prototype capable of participating in the ROBOCUP humanoid league [16] where a wide range of technologies need to be integrated and evaluated, giving added value for project-oriented education.

In this line of thought, the paper presents the design concepts and the technological solutions to build a small-size 22 degrees of freedom (DOF) humanoid robot at reduced costs, but still aiming at a fully autonomous platform for research. 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. The demands for limited costs gave rise to the selection of off-the-shelf materials and components.

The design and development of the autonomous humanoid platform has considered three phases:
- Definition of the functional and physical requirements, *i.e.*, mechanical structure, dimensions and degrees of freedom;
- Selection and integration of hardware and software to achieve these requirements;
- Development of low and intermediate level tasks (*i.e.*, hardware and sensor oriented).

Consequently, several technologies need to be integrated and a large number of technical breakthroughs must be accomplished. The most relevant achievements of this implementation include the distributed control architecture, based on a CAN bus, and the modularity at the system's level. On one hand, the key concept for the control architecture is the distributed approach, in which independent and self-contained tasks may allow a standalone operation. This feature allows for localised control capabilities based on feedback control from several sensors, ranging from joint position to force sensors. Moreover, the distributed computational power may allow for the development of sophisticated sensor fusion. On the other hand, a 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.

Though much work remains to be done in exploiting the potential of the proposed tools, the first results achieved at the present stage of development are also presented. The remainder of the paper is organised as follows. Section 2 describes briefly the humanoid platform, namely, the design and modelling considerations. Section 3 focuses on the actuators and the power concerns. Section 4 discusses the distributed architecture approach implemented. Section 5

presents the perception capabilities installed on-board of the robot. Section 6 concludes the paper and outlines the perspectives towards future research.

II. DESIGN AND MODELING CONCERNS

A- Mechanical design

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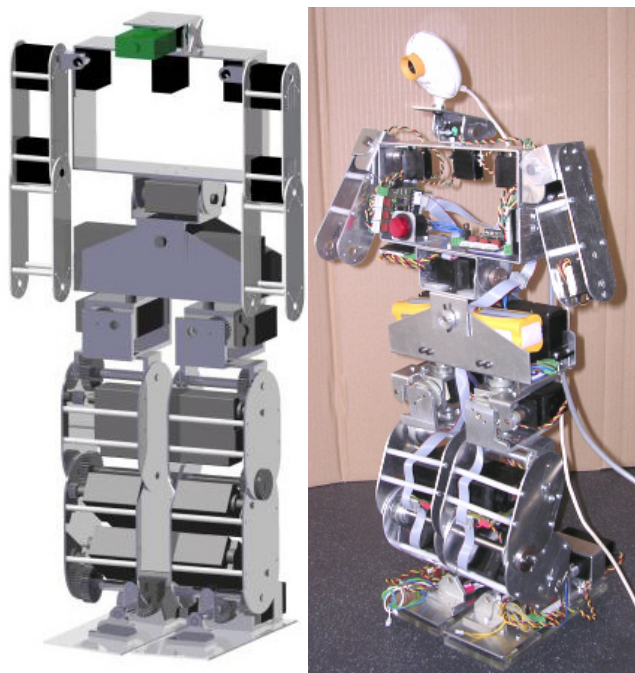

Fig. 1 - 3D model of the humanoid robot and current stage of implementation

After the structure height (60 cm) and remainder body proportions, the very first issue has been the number of degrees of freedom. In order to ensure proper and versatile locomotion, the robot is doted with six DOFs per leg, namely one universal joint at the foot, a simple joint on the knee and a spherical joint on the hip. Walking concerns can range from simply ensuring robust equilibrium to static walking up to, hopefully, dynamic walking for energetic efficiency. Connecting the legs to the upper structure of the abdomen was decided to be done with two DOFs mainly aiming at greater flexibility in balance control and account for the perturbations of the centre of mass (CoM). So far, arms have been only partially 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. This is a small-size robot with 22 DOF's, about 60 cm height and 5 kg

weight. The system was designed to be self-contained, low-priced, modular and expansible. For the dimensions involved, 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. In order to specify the adequate motors, several static simulations were carried out to estimate torques.

B- Kinematics modeling

Walking robots can be conceptually seen like serial robot arms, but accounting some serious differences. The main issues arise because these systems do not have their feet rigidly fixed to the ground and also due to changes in the structure during the walking cycle. The difficulty of handling structure-varying systems may depend on how the link connectivity of the mechanism is described. In this study, the humanoid robot is described as a couple of serial kinematics chains connected together in order to form a tree structure.

At a first stage, the robot is divided in lower and upper extremities parts connected through the trunk. During the single-support phase, the Denavit-Hartenberg (D-H) model consists of the interconnection of four kinematics serial structures, with the base coordinate systems at the supporting foot. During the double-support phase, the kinematics structure is divided at the middle point of the frontal plane to result in two separate D-H models. Hence, the Matlab model implemented is based on the superimposition of several open kinematics chains built using the D-H methodology.
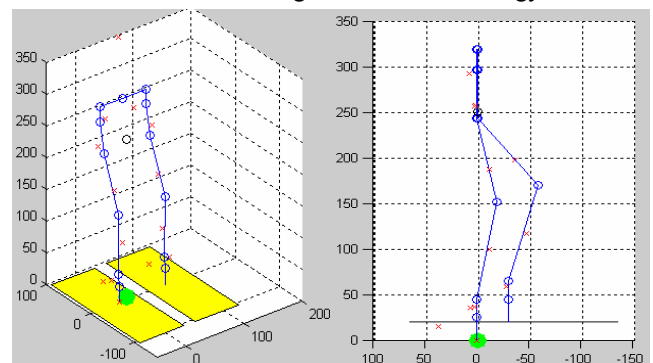

Fig. 2 – The Matlab kinematics model

C- Working angles and motor torques

The 3D structural model developed in CATIA provides the CoM of the several links of this multi-body system. The kinematics parameters, the masses and inertia tensors are then fed into a pseudo-static model developed in Matlab that computes all relevant variables along a sequence necessary to produce a locomotion step. Several basic motions were performed in order to estimate the working joint angles, the projection of the centre of gravity (COG) and the motor torques.

The trajectory for movement among given points in the working area is calculated from the inverse kinematics. First, two restrictions were imposed to eliminate redundancies: 1)

the upright vertical configuration of the pelvis section; and 2) the swing foot remains parallel to the ground. Second, the required torques were obtained using the well-known expression $T_k = \left\| \sum_{i=k}^{N} m_i \mathbf{r}_i \times \mathbf{g} \right\|$ 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 simulation results shown in Table 1 indicate that the most demanding situations occur at the ankle and hip joints responsible for lateral opening of the legs, showing up torques around 2.6 Nm. In Table 1 "tilt" means rotation in the sagital pane and "roll" means rotation on the frontal plane.

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

Motor/ Joint	θ_{min} [º]	θ_{max} [º]	T_{max} [N.m]
Foot 1 roll	−35	+35	**2.37**
Foot 1 tilt	−30	+60	0.30
Knee 1	−45	+55	1.17
Hip 1 tilt	−60	+60	0.35
Hip 1 roll	−70	+21	**2.57**
Foot 2 roll	−35	+35	0.00
Foot 2 tilt	−30	+60	0.12
Knee 2	−45	+55	0.30
Hip 2 tilt	−60	+60	0.14
Hip 2 roll	−70	+21	0.30

III. ACTUATORS AND POWER CONCERNS

A- Servomotors and their control

Static simulations made with the developed 3D model showed that some joints would require torques as large as 2.6 Nm in a typical simple gait. Common commercially available motors pointed to the HITEC servo-devices, but their highest torque is smaller than 2.3 Nm, which is the case of the HS805BB model.

To account for lower mechanical efficiency and larger safety coefficients, transmission gear ratios had to be inserted. This requirement complicates the mechanical design and, at the end, toothed transmission belts were used imposing gear ratios of about 1:2.5. Fig. 3 shows one of such transmission systems used on the humanoid foot.

A second problem concerning the servomotors is that they do not offer directly velocity control. Instead of changing the motor internals, as some other authors do, it was decided to implement velocity control by software. That is achieved by a variable PWM (pulse width modulation) throughout the full excursion of a joint.

In other words, the software tracks motor position with time and adjusts the PWM in order to accelerate or pause motor motion. The results are not optimal for lower speeds since it results in non continuous motor motion, but for preliminary results that is enough. Further developments will

possibly require better performance, for instance, by replacing the electronics control unit of the motor package.
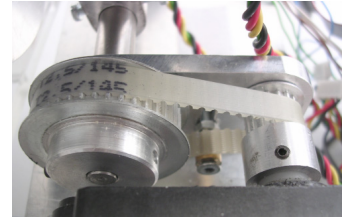

Fig. 3 - Transmission belt with an adjustable tensile roller.

Concerning power, there are no clear official indications of the power of the servomotors, which is an important issue for velocity/torque performance. Experimental results point to a overall electric power maximum consumption of circa 12 W, which, of course, translates in less than that for usable mechanical power due to electrical and friction losses.

B- Batteries

Power to drive the motors is a central issue since servos require a high current, namely at start-up 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 batteries weights circa 176 g and confines to a box of 37x37x65 mm³. Proper fusing, polarity protection and charge monitoring were also implemented. Later on, polarity protection was removed since the power diode used dropped voltage by more than 1 V, affecting some parts of the circuits ahead when batteries discharged for a while.
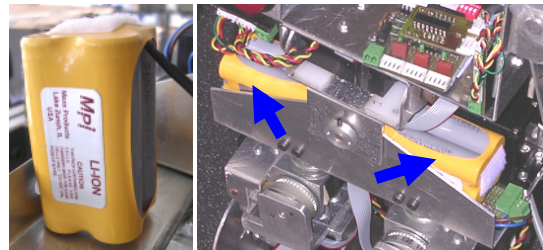

Fig. 4 – Batteries and their location on the robot

Fig. 4 shows the selected batteries and their location on the robot. The location chosen to install the batteries followed the rule: the lowest place on the robot where they would fit. Of course, legs could be enlarged to accommodate batteries, but that would also imply mechanical trade-offs regarding proportions and, worst of all, lower the CoM, which is not advisable for ROBOCUP competition since that is mentioned in the rules. Furthermore, having a high CoM will promote dynamic walking instead of static walking only, as the project is still confined to.

IV. THE DISTRIBUTED ARCHITECTURE APPROACH

In order to have a flexible control system, a distributed architecture has been devised. The system joints have been grouped by vicinity criteria and are controlled locally by a

dedicated board inserted in the CAN bus using a slave configuration. A master unit relays all slave units by dispatching medium and high level orders and by collecting sensorial data to be eventually processed on a central unit, which interfaces the master controller by a serial RS232 link. The central unit is currently an off-board computer but will be migrated to a local controller (possibly a PC104 based) with image processing capability. Fig. 5 shows a generic diagram of controlling units.
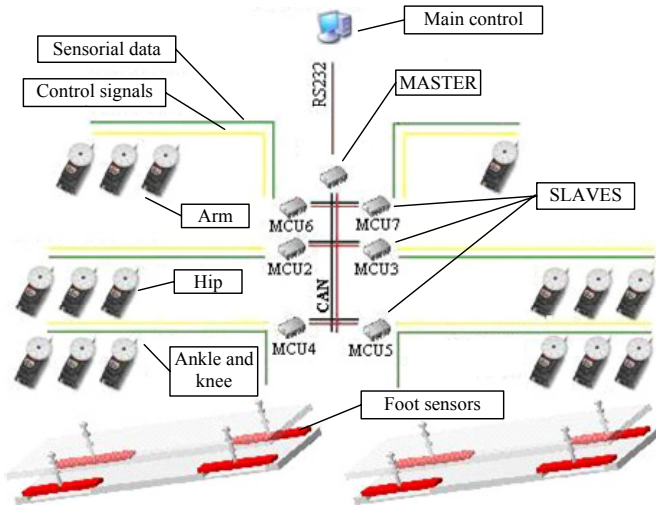

Fig. 5 - General architecture layout

Although RS232 may seem slow, the relevant fact is that it will not be used to close the low-level control loops of the robot. Only motion directives and some sensor status are to be exchanged. Even in an unlikely worst-case scenario requiring continuous information for all motors and gathering information from all sensors, circa 20 full cycles per second would be possible at 38400 baud.

A- Hardware for the units in the architecture

Master and slave units are based on a PIC microcontroller. Slaves are all alike and can be distinguished by a configurable address. Slaves can drive up to 3 servomotors, and can monitor their angular positions and electrical current consumption. Concerning additional sensors, each slave unit has the possibility of accepting a piggy-back board where additional circuit can lay to interface to other sensors. Some examples of the developed piggy-back boards include force-sensors, accelerometers and gyroscope.

Fig. 7 shows a generic diagram of a slave unit. There, the main internal blocks can be seen, such as power supply regulation, CAN interface, the PIC controller, the multiplexer for sensor interfacing, PWM lines, CAN address switches and also lines prepared for RS232 communication. This kind of layout allows high versatility both on hardware and software approaches.

Being all similar, the construction of the boards is easier, along with software development (the same base code for all units). The master unit is different since it is not expected to

drive motors neither to acquire many sensorial data. Furthermore, it communicates both by CAN and serial RS232 to the upstream controller. Hence, its piggy-back module was used to interface electrically the RS232 communications by installing a MAX232 circuit instead of sensor acquisition.
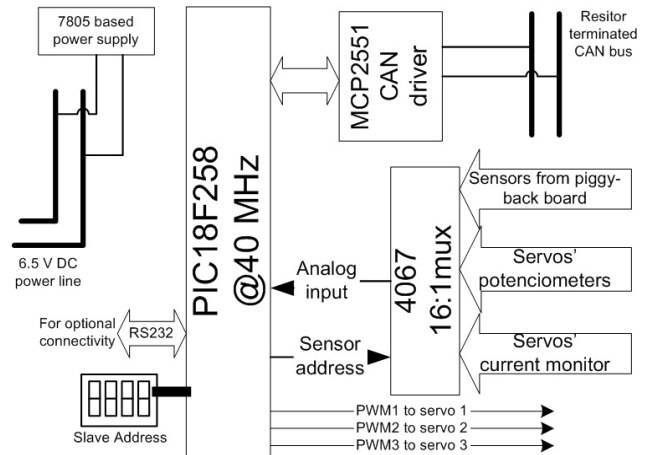

Fig. 7 - Block diagram of generic slave unit

Slaves will be able to perform local control when adequate algorithms will be developed. In the slave units, three PWMs are generated for the three servomotors with resolutions of about 1 μs according to directives received from the CAN bus, but in the future local algorithms may decide better how to control the motors instead of relying on central control. Still at the slaves, the sensorial data is currently acquired with 8 bits,
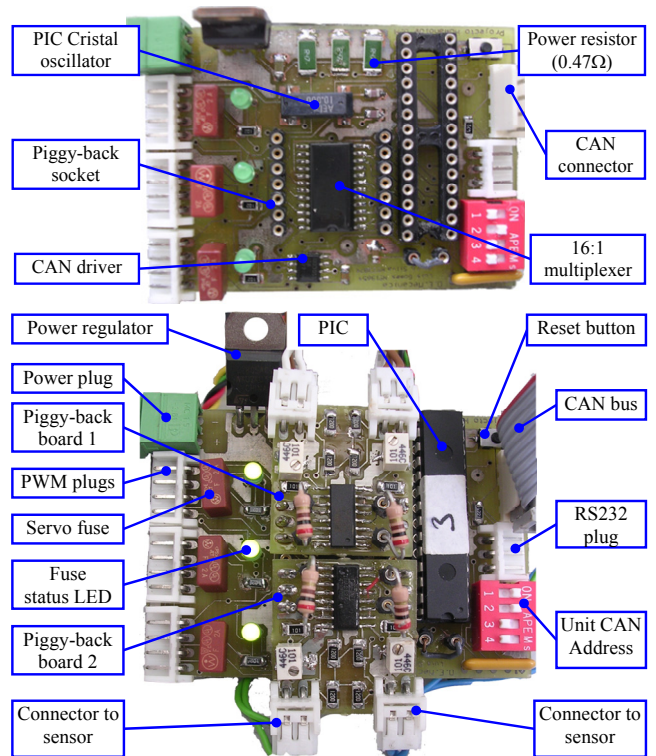

Fig. 6 – The slave processing board without most components (up) and in full mounting with two piggy-back boards for force sensors (down).

but 10 bits are possible in case it becomes necessary and adequate signal filtering and conditioning is provided. Fig. 6 shows a slave unit PCB with the main components and also includes a piggy-back board for signal electric conditioning. Currently, only the master uses the RS232 plug. It is used to communicate with main control unit; slaves do not use it for now but it is there for future developments or debug.

B- Communications: CAN and RS232 messages

In the current stage of development, on power-up or reset, each slave checks its address and starts monitoring the CAN bus. While no messages arrive, the slave unit will drive its joints to a home position at a reduced speed and starts monitoring local sensors at a given rate (pre-programmed). When messages from the CAN bus arrive, the slave unit will process them; messages are of two kinds: imposing new desired position and speeds to each of the three motors, or query for sensorial data. These requests come from the master only and at a rate imposed at 10 kHz. Currently the system has 8 slave units; assuming one message for each slave and 2 messages back for the master from each slave, this results in a more than 400 Hz [10000/(3×8)] full cycle at the architecture intermediate level; actuators are controlled locally with much finer resolution. The CAN bus is driven at 1 Mbit/s.

CAN messages contain a data field with 8 bytes, enough to exchange (in one message only) orders for three servos (3 positions and 3 speeds). On the other hand, to gather data from the slaves, more than one message may be necessary. Indeed from 3 motors 6 variables are required (3 positions and 3 current levels), and additional sensor values (such as force or inertial) must go on other messages.

The master keeps a current status of the full system and delivers that data to the main control unit when requested by the RS232 link. Currently, this protocol defines a 3-byte message to master and a 6-byte message from master to control unit.

V. SENSORS AND PERCEPTION

Perception assumes a major role in an autonomous robot, therefore it must be reliable or abundant, or both if possible! For this platform the following perception was planned:

- Joint position (reading servo own potentiometer)
- Joint motor current (related to torque)
- Force sensors on the feet (ground reaction forces)
- Inclination of some links (using accelerometers)
- Angular velocity of some links (using a gyro)
- Vision unit (located on top)

Up to now, only vision has not yet been approached. The remainder sensors were addressed with different levels of accuracy, but all potentially usable with current hardware. Joint position is currently read directly from the servomotor potentiometer. That signal, however, presents instability when the motor is moving which may affect measurement. Possibly in future developments an external potentiometer or encoder is to be used. Electric current consumption is easily measured as

the voltage on the resistor (0.47 Ω) in series with the servo. Now follow details on force and inertial sensors.

A- Foot force sensors

The foot sensors are intended to measure the force distribution on each foot to further assist during locomotion or simply keeping upright. Moreover, it is expected to use that information for future local control, and some work is already on the road [17].

Four sensors on each foot will allow balance evaluation both on static and dynamic motion. Commercial force sensors are expensive, so it was decided to develop a system based on strain gauges and to amplify the deformation of some stiff material. The result is a kind of foot, whose details can be viewed in Fig. 8, based on 4 acrylic beams located on the four corners of each foot that deform according to the robot posture. A simple Wheatstone bridge and an instrumentation amplifier complete the measuring setup (Fig. 9). The electronics hardware lays on a piggy-back board mounted on the slave unit, as can be seen in the lower part of Fig. 6.
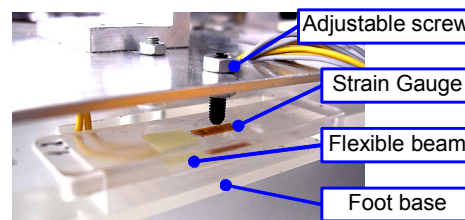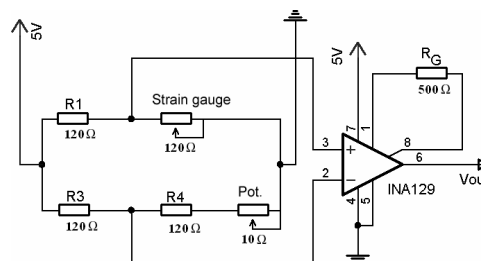

Fig. 8 - Foot sensor details

Fig. 9 – Circuit to measure force on the feet

B- Inertial devices

Inertial perception is also a relevant source of information for dynamic and also static locomotion and balancing. Accelerometers and gyroscopes furnish information on acceleration and angular velocity.

Concerning accelerometers, they can be used to measure the acceleration of gravity, or better said, its component aligned with some axis. In other words, they can be used to measure inclination; however, this is only true in static positions or for very slowly accelerated motions. Nonetheless, the inertial information provided by accelerometers can be exploited in the future with software yet to develop. The accelerometer chosen was ADXL202E from Analog Devices and was interfaced with a circuit similar to one suggested by the vendor datasheet. This very small MEMS device has two accelerometers in orthogonal axis that can be used to monitor

tilt and roll angles of the platform. The system was mounted on a small PCB as shown in Fig. 10. The sensor provides information both in analogue and digital form, which is also an advantage to exploit in other developments.
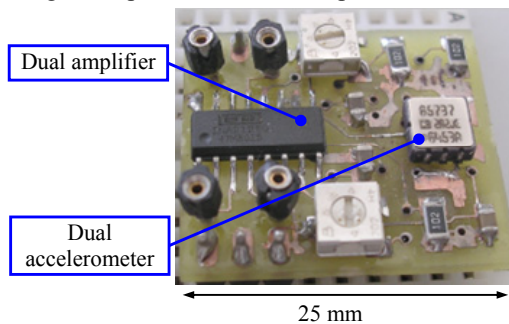

Fig. 10 - Piggy-back board with two accelerometers

Finally, in what concerns sensors, a gyroscope unit has also been developed. The GYROSTAR ENC-03JA from MURATA has been selected for several reasons: ease of interfacing; high angular velocities (±300º/s), relatively high response (50 Hz), low cost and commercial availability. Up to now, the unit has not yet been used in practical control of the developed platform. Its circuit is simply adapted from the vendor datasheet and using a INA129 amplifier.

VI. CONCLUSION AND PERSPECTIVES

This paper covers the technological and engineering solutions to build a humanoid robot based on off-the-shelf inexpensive components. The principal features of the 22-DOF system include a distributed control architecture with local control possibility, based on a CAN bus, and is prepared to use many types of sensors, from joint position monitoring to force sensors on the feet. Foot force sensors were developed using 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. Nonetheless, some improvements on some hardware parts are already scheduled; that includes additional safety issues to automatically cut power on a given control unit when failure occurs either by software of power fluctuations. Professional manufacturing of hardware (namely electronics) may be soon a possibility, but it will necessarily increase costs, and must be clearly evaluated.

Ongoing developments cover the inclusion of vision and its processing, possibly with a system based on PC104 or similar. Currently, what has been developed is simply 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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