The NAO humanoid: a combination of performance and affordability

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***Abstract*—This article presents the design of the autonomous humanoid robot called NAO that is built by the French company Aldebaran-Robotics. With its height of 0.57 m and its weight about 4.5 kg, this innovative robot is lightweight and compact. It distinguishes itself from its existing Japanese, American, and other counterparts thanks to its pelvis kinematics design, its proprietary actuation system based on brush DC motors, its electronic, computer and distributed software architectures. This robot has been designed to be affordable without sacrificing quality and performance. It is an open and easy-to-handle platform where the user can change all the embedded system software or just add some applications to make the robot adopt specific behaviours. The robot's head and forearms are modular and can be changed to promote further evolution. The comprehensive and functional design is one of the reasons that helped select NAO to replace the AIBO quadrupeds in the 2008 RoboCup standard league.**

Fig. 1. Aldebaran-Robotics NAO humanoid.

I. Introduction

WHY build another humanoid robot? This introduction will answer this question by describing the four guidelines the French company Aldebaran-Robotics [1] [1] followed in the design and making of the NAO humanoid robot (figure 1). These guidelines are affordability, performance, modularity and open architecture.

Affordability means that the robot should be made available to the maximum of people who would like to work or play with a performant biped robot. Currently the cost of such robots is dissuasive for labs or research teams that cannot build reliable legged robots. Functional robots must be devised by researchers and engineers, but they must be manufactured by specialized companies to ensure good industrial integration. Among performant robots the Asimo humanoid built by Honda may be the most impressive [2], [3]. It is capable of walking fast, up to $3[km/h]$ forward, change direction and walk up/down stairs smoothly. It can even reach $7[km/h]$ by adopting a special running gait. It can also react to external disturbances by adjusting its posture to keep stability. The HRP-2 robot manufactured by Kawada Industries is also a good technological achievement [4]–[6]. It can walk up to $2.5[km/h]$, and can lie down and get up again by itself. Thanks to extensive government funding these Japanese humanoid robots are developed to promote research in the area of assistance robotics. Their successors [7] should help people in their every day life or achieve tedious tasks in the place of humans. The size of these robots must be compatible with human-scale environments.

[1]Aldebaran-Robotics is a French company founded in 2005 by chief executive Bruno Maisonnier.

However these robots were either not available to researchers or only available to the few teams that have enough funding to support the cost and maintenance of such robots. Functional humanoids are somewhat expensive (see table I). Even the HOAP small-sized humanoid robot from Fujitsu costs about $50K$ US \$. The NAO robot has been devised with the concern of cost reduction without sacrificing quality and performance. It is a completely custom designed robot as the whole process of design and manufacturing is mastered (mechanics, electronics, software). This allowed costs to be reduced at every stage of design. The company employs subcontractors to produce plastic parts or electronic circuits on a large scale. One way to achieve cost reduction was the reuse of the same actuator modules for several joints. Another way consisted of reducing the number of motors without sacrificing mobility. The robot will cost about 10K euros for laboratories. Thanks to mass production and reduction of functionalities a version will be publicly available for approximately 4K euros.

A biped robot must show good motion performance for

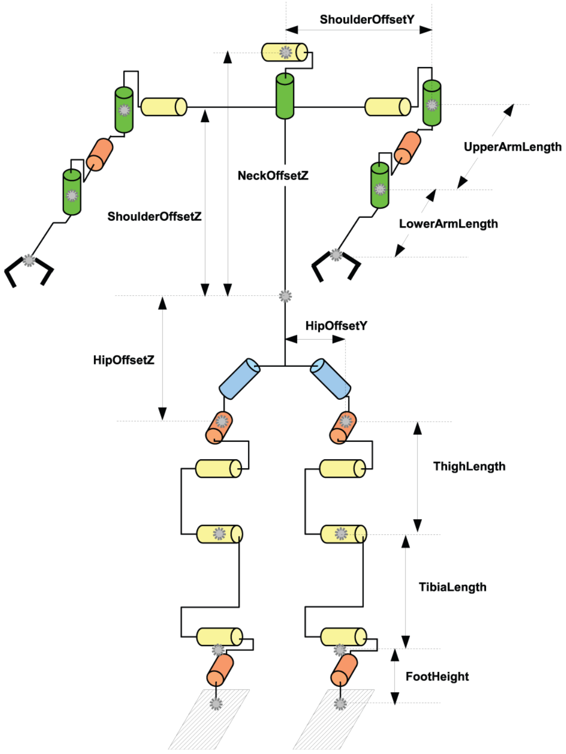

Fig. 2. Detailed kinematics of NAO. Wrist joint not represented.

its height to weight ratio or body mass index (BMI). NAO has a BMI of about $13.5[kg/m^2]$, which means that it is very light compared to other existing robots of the same height. Table I gives the BMI for different functional humanoid robots. The quest for NAO performance is different from the objectives followed by teams of robotics laboratories who focus on a particular research subject. One subject concerns the development of walking gaits on biped or humanoid prototypes, like the ETL-humanoid [8], the BIP biped [9], the 2D Rabbit biped [10], or the Johnnie and LOLA humanoid robots [11]–[13]. Other studies aim at designing robots with artificial limbs for disabled people, like the Robian biped [14], or at exploring natural dynamics of flexible actuators, like the series of robots designed at MIT [15].

First, the performance targets for NAO are smooth walking gaits even when changing speed and direction, and a rich panel of movements that the robot must execute with smoothness and precision. The walking speed must be similar to the walking speed of children of the same size, that is about $0.6[km/h]$. These objectives of performance involve building strong and reliable hardware together with precise joint control. The robot was equipped with high quality brush DC motors and high precision magnetic sensor devices. For each motor the gear reduction mechanism was carefully optimized.

Further, the robot must be equipped with cognition and artificial intelligence capabilities, but above all, interactive autonomy. This supposes that the robot is able to recognize features and human faces in the environment, to self-localize and to operate in this environment. One of the big challenges for a legged robot consists of self-localizing and

TABLE I
CHARACTERISTICS OF FUNCTIONAL HUMANOIDS.

	Height (h) (m)	Weight (w) (kg)	BMI (kg/m^2)	Price
KHR-2HV	0.34	1.3	10.9	1K US $
HOAP	0.50	7.0	28.0	50K US $
NAO	**0.57**	**4.5**	**13.5**	**10K euros**
QRIO	0.58	6.5	19.0	NA
ASIMO	1.30	54.0	32.0	NA
REEM-A	1.40	40.0	20.4	NA
HRP-2	1.54	58.0	24.5	400K US $ (5 year lease)
Human	1.5-2	50-100	18-25	NA

BMI: body mass index = w/h^2, NA: not available

recognizing moving objects while walking. This is one of the preoccupations of the participants to the RoboCup competition legged league [16]. Some research teams have already built humanoids dedicated to studying autonomous interaction with humans and the environment, such as the Japanese JSK-H7 humanoid [17], or the recent REEM-A and REEM-B humanoids [18] [19]. For NAO to interact with its environment, the head was equipped with interactive sensors (see table II). It is clear that the cognitive capabilities of the robot will depend on the quality of the embedded software.

Modularity is the third guideline followed by the French designers of NAO. Firstly, modularity refers to actuator modules that could be used for different joints. This was also the concern of designers of the LOLA bipeds [13] or the QRIO humanoid [20]. For NAO, there are four kinds of actuator based on two types of brush DC motor and two types of gear reduction for each motor. Secondly, the modular design of the robot's limbs is also very useful to promote further evolution. Modular design was used by SONY for the ERS-2xx versions of AIBO quadrupeds [21] used in RoboCup. Legs and head could be changed quickly in case of trouble. Legs could also be replaced by wheels or other limbs. In the case of NAO the head can be easily unplugged and replaced by a more specialised one. Hands and forearms can also be changed. Thirdly the problem of maintenance is not negligible, especially in the case of human-size robots such as HRP-2 [6], or small-size sophisticated humanoids such as SDR-4x/QRIO [22]. Since NAO will be for sale on a large scale, its maintenance must be optimized so that spare parts can be changed quickly. The modular design should help maintenability and increase the robot's reliability.

The last guideline refers to open architecture. Open architecture means that the robot must be easy to get started with and to handle. This involves ergonomic software for a maximum of people to access and understand the programming functions, even for people who are not experts at programming. Some existing humanoid robots suffer from this lack of ergonomy The software proposed with NAO is user-friendly and relies on a distributed architecture that allows interfacing with embedded and remote applications that are useful for debug and development. Open architecture also means that the majority of the embedded software including the operating system can

TABLE II
SENSORS THAT EQUIP NAO.

Type	nb
30 FPS CMOS videocamera	1
Gyrometer	2
Accelerometer	3
Magnetic rotary encoder (MRE)	34
FSR	8
Infrared sensor (emitter/receiver)	2
Ultrasonic sensor	2
Loudspeaker	2
Microphone	4

TABLE III
MAIN CHARACTERISTICS OF THE NAO HUMANOID.

Body	
Height (m)	0.57
Weight (kg)	4.5
Battery	
Type	Lithium-ion
Capacity	55 Wh
Degrees of freedom (DOF): 25	
Head	2 DOF
Arms	5 DOF X 2
Pelvis	1 DOF
Leg	5 DOF X 2
Hands	1 DOF X 2

Masses $[g]$	
Chest	1217.1
Head	401
Upper Arm	163
Lower Arm	87
Thigh	533
Tibia	423
Foot	158
Total	4346.1

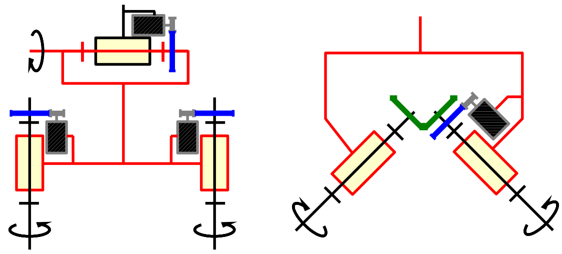

Fig. 3. Left-hand side: classical set of three rotary joints, one horizontal axis rotary joint at the waist and two vertical axis rotary joints for the legs. Right-hand side: coupled inclined axis rotary joints for the NAO pelvis.

TABLE IV
JOINTS TYPE, RANGE, AND ACTUATOR TYPE.

Part	Motion	Range (°)	Actuator type
Leg (left)	hip twist (45°)	-68 to 44	M1R11
	hip roll	-25 to 45	M1R11
	hip pitch	-100 to 25	M1R12
	knee pitch	0 to 130	M1R12
	ankle pitch	-75 to 45	M1R12
	ankle roll	-45 to 45	M1R11
Arm (left)	shoulder roll	0 to 95	M2R22
	shoulder pitch	-120 to 120	M2R21
	elbow roll	-120 to 120	M2R22
	elbow yaw	0 to 90	M2R21
Head	yaw	-90 to 120	M2R21
	pitch	-37 to 31	M2R22

be changed by the user if desired. Low level hardware access is also open to allow users to change joint control laws. Some companies that have built humanoid robots available for purchase do not propose such features, and limit the access and possibilities of changing the embedded software.

This paper focuses on the design of the NAO humanoid biped, that was designed to be affordable and performant. Cost, performance, modularity, and open architecture were the four guidelines followed by the French designers of the Aldebaran-Robotics company. The outer shell was specially designed for the robot to look friendly. The first section of this paper is dedicated to the mechanical design and describes kinematics and actuation system. The second section deals with the electronic and computer architecture. The third section is devoted to the software architecture specially developed for NAO.

II. MECHANICAL ARCHITECTURE

Table III gives the main characteristics of the NAO humanoid.

A. *Kinematics*

NAO has a total of 25 degrees of freedom, 11 degrees of freedom (DOF) for the lower part that includes legs and pelvis, and 14 DOF for the upper part that includes trunk, arms and head.

Each leg has 2 DOF at the ankle, 1 DOF at the knee and 2 DOF at the hip. A special mechanism composed of two coupled joints at each hip equips the pelvis. The rotation axis of these two joints are inclined at 45° towards the body. This mechanism replaces the classical set of three active rotary joints encountered in most humanoid robots (see figure 3). This classical set includes the horizontal axis rotary joint at the waist and the rotary joints of vertical axis for each leg hip. Only one motor is required to drive the pelvis mechanism of NAO. This allows to save one motor at hip level without reducing the overall mobility. The mechanism permits NAO to bend the body forward while spreading the legs simultaneously. It is therefore useful for sitting down and for bending to grasp or lift something on the ground. This mechanical design was registered for patenting [23]. Unlike prototypes such as H7 [24], Wabian-2R [25] or LOLA [13], the foot sole of the present version of NAO does not feature any passive or active joint that would enhance higher speed gait performances [26].

In addition, each arm features 2 DOF at the shoulder, 2 DOF at the elbow, 1 DOF at the wrist and 1 additional DOF for the hand's grasping. The head can rotate about yaw and pitch axes. Figure 2 gives the kinematics details, and table IV lists the joints with their range.

B. *Dimensionning of leg actuators*

Some humanoid designers developed an iterative process of mechanical design and dynamic simulations to get parameters of joint torques and velocities that were used for motor and gear selection [13]. The design process of NAO is not iterative and relies on a dimensioning methodology. The robot's model is simplified and simulated dynamically in the sagittal plane and in the frontal plane. The software used for simulation was WorkingModel linked with Matlab-Simulink for the control part. A set of basic movements in the sagittal plane for the one part, and in the frontal plane for the other part, were defined and simulated. Movements in the sagittal plane helped dimension the knee actuators and the pitch joint actuators of hips and ankles. Movements in the frontal plane helped complete the dimensioning of hip and ankle roll joint actuators. The duration of each movement was set for the robot to achieve lively motion. Motor and gear selection must ensure that the robot will be capable of achieving these movements.

The robot's model in the sagittal plane is composed of a rectangular trunk and a single leg with rectangular femur, tibia and foot. The model in the frontal plane features both legs. Hip, knee and ankle joints are rotary joints. In the frontal plane knee joints are blocked. The set of basic movements in the sagittal plane are the following:

1) knee flexion on the spot, $1[sec]$ (fig. 4),
2) standing up from flexed knee position, $1[sec]$ (fig. 4),
3) leg transfer during walking step, body motionless, $1/3[sec]$ (fig. 5),
4) body translation in the direction of motion during leg stance, $1/3[sec]$ (fig. 5),
5) body sinusoidal movement in the direction of motion during leg stance, $1/3[sec]$ (fig. 6),
6) simultaneous knee flexion and body forward bending for pick up, $1.2[sec]$ (fig. 6).

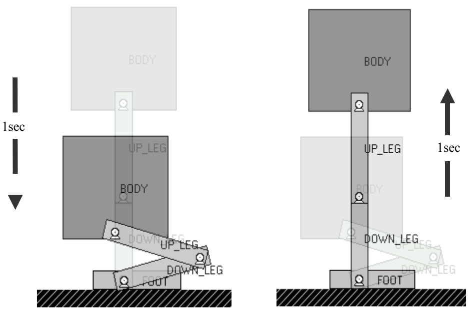

Fig. 4. Sagittal plane simulation experiments of knee flexion (1) and stand up (2).

The set of basic movements in the frontal plane are the following:

1) lopsided move on both legs, $0.5[sec]$ (fig. 7),
2) leg lift off in lopsided position , $0.5[sec]$ (fig. 7),

All motors are controlled using a PID law. Velocity and output torque are recorded for all the movements. Actuator power is also recorded. For each joint the data relative to all the simulated movements are grouped to get the velocity variations as a function of torque over all the movements. Then the convex envelop is calculated. Figure 8 presents the curves of speed vs torque relative to the knee joint for experiments 1 to 6 in the sagittal plane. The convex envelope is also represented.

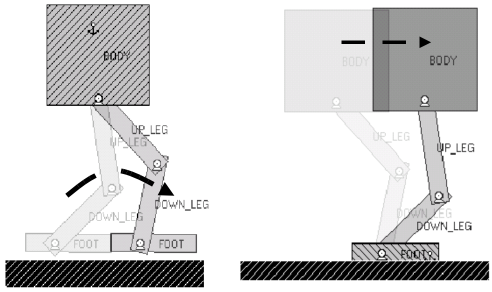

Fig. 5. Sagittal plane simulation experiments of one step leg transfer (3) and body translation (4).

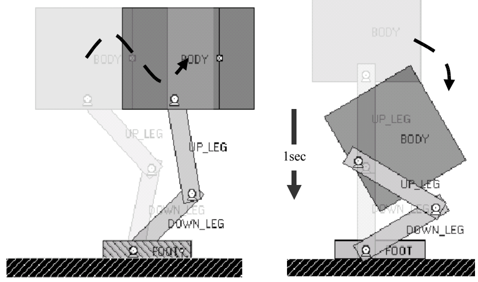

Fig. 6. Sagittal plane simulation experiments of body sine move (5) and pick up (6).

The rpm versus torque specifications of off-the-shelf motors were compared with the desired variations to select the best suited motors. For this purpose a special graphical interface was developed to display the convex envelopes of the speed versus torque requirements drawn from the simulated experiments, and the speed versus torque specifications of existing motors. It is possible to vary the power voltage, the reduction ration, the number of reduction stages, and to see the influence of these changes on the different parameters such as yield and on the speed vs torque curve. Figure 9 shows the speed vs torque specifications of two motors, one from Maxon and the other from Mabuchi. The convex envelopes are relative to the knee, hip, and ankle pitch joint data drawn from the family of experiments simulated in the sagittal plane. This study is very helpful to select the best motor that can be used for several joints.

After dimensioning it is interesting to check the load to motor inertia ratio k.

$$k = \frac{J_L}{N^2} \cdot \frac{1}{J_M} \tag{1}$$

where N is the reduction ration, J_M is the motor inertia, and J_L is the load inertia.

A too high value of load to motor inertia can cause instabilities and oscillations due to resonance. The more compliant the system, the more subject to oscillation it will be. A low value of the load to motor inertia leads to easier control and better dynamic response (fast acceleration/deceleration), but reduces the bandwidth of the system. Therefore the load to motor inertia results from a trade-off. Whatever the value of k, the most important parameter for actuators is the stiffness

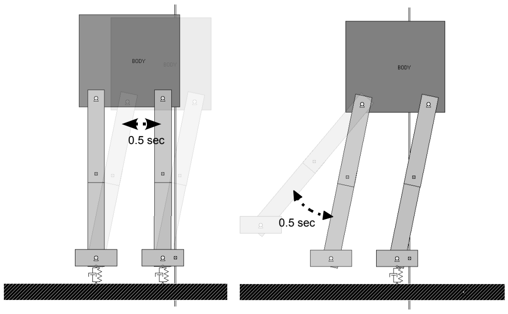

Fig. 7. Frontal plane simulation experiments of sideways move (7) and leg lift-off in lopsided position (8).

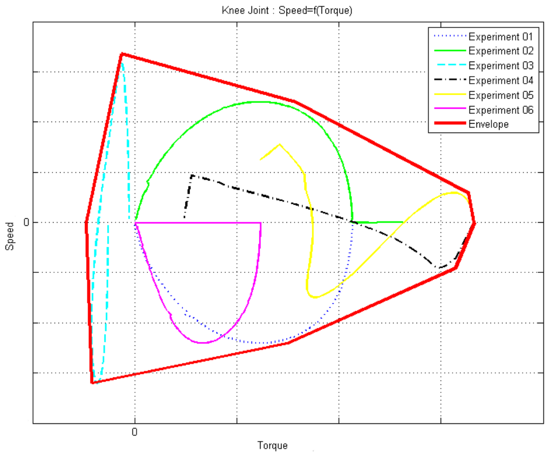

Fig. 8. Speed versus torque of knee actuator relative to experiments 1 to 6 in the sagittal plane.

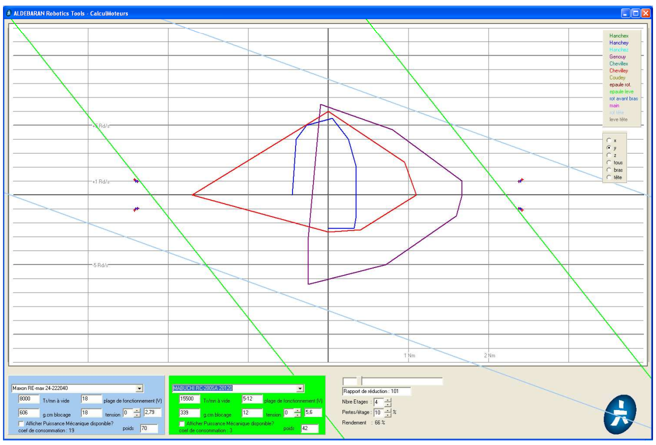

Fig. 9. Software used to choose motor and reduction ratio for the hip, knee and ankle pitch actuators.

of the gear mechanism. If the actuators are stiff enough, high values for the load to motor ratio are acceptable, as the control module can deal with close loop corrections. Taking into account that the drive mechanism is made of flat plane gears, the load to motor inertia ratio should be comprised between 1 and 10. Since the load varies when the robot walks, the ratio will vary inside this range.

Let us check the load to motor inertia ratio at the knee joint in the case of simple support and in the case of double support. The mass seen above the knee is the mass of the robot's upper part and the masses of the thighs, that is approximately $M = 3.2[kg]$, see table III. For the robot's lower part, the actuators are based on motor M1 whose inertia is $J_m = 4.17.10^{-7}[kg.m^2]$, and reduction ratio N is 130.85. The distance d of the knee joint to the center of mass is around $0.15[m]$ in the standard upright position. In the case of double support, we consider that each knee supports half of the mass M,

$$k_d = \frac{M/2.d^2}{N^2}.\frac{1}{J_M} \approx 5 \quad (2)$$

In the simple support phase, the load inertia must take into account the mass of the robot's upper part, the thigh of the supporting leg and the mass of the leg in the air. We assume that the position of COG does not vary.

$$k_s = \frac{(M - m_{tibia} - m_{foot}).d^2}{N^2}.\frac{1}{J_M} \approx 8.3 \quad (3)$$

The values of load to motor ratio are within the acceptable range.

C. Modular actuator unit design

The use of off-the-shelf RC servomotor modules was discarded from the beginning because they limit the performance of biped robots for a number of reasons: packaging not suited and generally bulky, gear reduction mechanism and joint control fixed.

Taking into account that actuators represent the major cost it is necessary to conduct a careful study of how to choose and assemble motor, driving mechanism and sensor in the same module. Fukushima et al. [27] listed the properties of a good actuator in their design of the ISA-4 –Intelligent Servo Actuator – for the SONY SDR-4X robot. The actuator must be compact, lightweight, highly back-drivable, efficient, precise and reliable. Backdrivability was studied by [20], it defines the facility of movement transmission from output to input axis. The performance criteria of an actuator are power over weight ratio, temporary high torque generation, bandwidth, and response time.

Among the specifications for NAO the response time of the actuator τ must be maximized by:

$$\tau \leq \Delta\theta_{max}/\omega \quad (4)$$

where ω stands for the maximal output angular velocity. The value of $\omega = 6[rad.s^{-1}]$ is set according to the desired times needed to achieve planned motion trajectories in the Cartesian space. $\Delta\theta_{max}$ is the maximal angular delay that can be authorized as a consequence to a slope command assigned at the ankle joint (see figure 10) when the robot is moving while having one leg in support. Taking into account a maximal deviation of the COG ground projection from the foot center, the maximal angular delay is set to:

$$\Delta\theta_{max} = \arcsin(\eta.L_f/L_G) \quad (5)$$

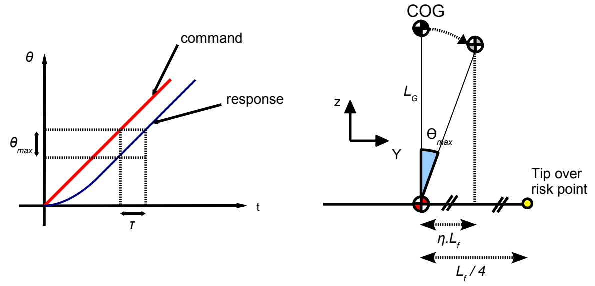

Fig. 10. Left-hand side: response to slope command assuming first order system for the actuator mechanism. Right-hand side: determination of maximal acceptable angular deviation.

where L_G is the distance between ankle and COG, l_f is the foot width, and η is the margin of foot width accepted for the maximal deviation related to command delay. The command delay should leave the possibility for the robot to react before it tips over. With $\eta = 1/8$, $L_f = 0.125[m]$, and $L_G = 0.27[m]$, the response time τ must be less than $6[ms]$. In addition, the angular joint backlash must remain between $-3°$ and $3°$. These values were set according to the maximal distance the COG can move from the upright position when tilting about the ankle with knee stretched. Usually this distance is set to be one quarter of the foot length in the case of static equilibrium.

Off-the-shelf motors for legged robots do not exist. Designers of humanoids usually use existing brush DC motor [4], [5], [11], brushless DC motor [13], or proprietary motors [27]. Brushless DC motors present a better power density, higher torque and speed bandwidths compared to brush DC motors. However the electronics is more complex and therefore more expensive. The motors used for the NAO actuators are Maxon coreless brush DC motors, that are known for precision and reliability.

Even though harmonic drives are widely used for human-size humanoids [13], they were not selected because they remain expensive, and there were not many providers. In addition off-the-shelf harmonic drives do not present enough backdrivability [20] and the reduction ratio is very high. In the case of the HRP-2, harmonic drives were used in conjunction with timing belt and pulley. Taking this into account the designers of NAO decided to use spur and planetary gears in order to have a fairly good backdrivability. This strategy was also adopted for the development of the ISA actuators [28]. These kinds of gear offer very small backlash. In addition special plastics loaded with PTFE (Polytetrafluoroethylene) and carbon fiber were used to meet torque and longevity requirements.

Investigating velocity as a function of required output torque yields to choose motor and gear reduction ratio for each joint. Thanks to a comprehensive study the number of actuators is reduced to 4 for all the joints. There are 2 kinds of motor, M1 and M2, and 2 types of reduction gear for each motor, R11 or R12 associated with M1, and R21 or R22 associated with M2. Tables V and VI give the technical details for both actuator types. The innovation brought to the design of the NAO actuators (registered for patenting [29]) consisted of

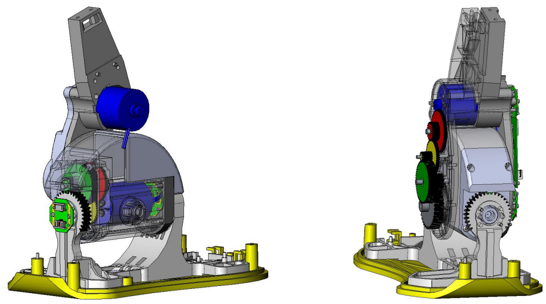

Fig. 11. CAO design of ankle module

TABLE V
ACTUATOR 1 SPECIFICATIONS

Characteristics	Motor type 1	Reduction	
	M1	R11 ratio = 201.3	R12 ratio = 130.85
No load speed	8000 RPM	238.45°/s	366.83°/s
Stall torque	59.5 mNm	11.97* Nm	7.78* Nm
Nominal speed	6330 RPM	188.67°/s	290.25°/s
Nominal torque	12.3 mNm	2.47* Nm	1.61* Nm

**: without ratio efficiency*

TABLE VI
ACTUATOR 2 SPECIFICATIONS

Characteristics	Motor type 2	Reduction	
	M2	R21 ratio = 150.27	R22 ratio = 173.22
No load speed	11900 RPM	473.72°/s	412.19°/s
Stall torque	15.1 mNm	2.27* Nm	2.61* Nm
Nominal speed	8810 RPM	351.77°/s	305.16°/s
Nominal torque	3.84 mNm	0.57* Nm	0.66* Nm

**: without ratio efficiency*

grouping two rotary joints together to make a Universal joint module that includes packaging. This allowed costs to be reduced and to take into account the mechanical constraints imposed by the outer shell. Thus the same Universal joint module composed of actuators M2R21 and M2R22 is used for shoulders, elbows and head. Regarding the lower part of the robot, the same motor M1 is used for the pelvis joint and all leg joints, the gear mechanism R11 is the same for pitch joints and the pelvis joint, and R12 is the same for roll joints. However the module packaging differs according to the left or right-hand side. Figure 11 gives a CAO view of the ankle joints module.

III. COMPUTER - ELECTRONICS ARCHITECTURE

A. Computer architecture

NAO's head is equipped with an x86 AMD GEODE 500 MHz CPU motherboard with 256 Mb SDRAM. An additional 1Gb Flash memory is available. Communication with the robot is possible through WiFi 802.11g protocol and through Ethernet port. The CPU manages audio, video, and WiFi and other advanced modules. One ARM7-60MHz microcontroller located in the torso distributes information to all the actuator module microcontrollers (Microchip 16 bit dsPICS) through

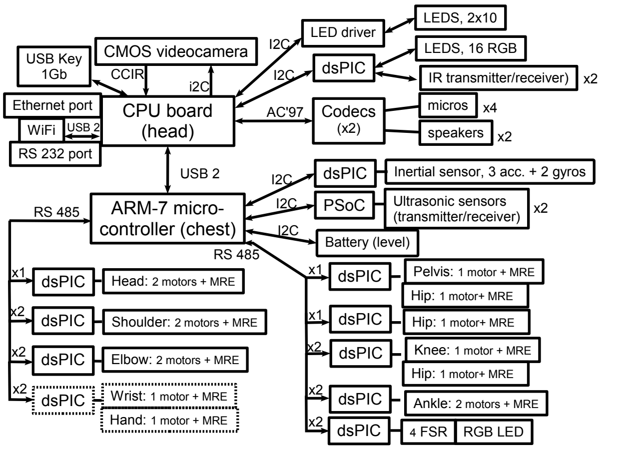

Fig. 12. Electronic architecture of NAO. MRE stands for magnetic rotary encoder.

a RS485 bus (throughput of $460[Kbits/s]$). There are two RS485 buses, one that connects the ARM7 microcontroller to the dsPICS modules of the upper part of the body, and the other that connects the ARM7 to the dsPICS modules of the lower part of the body. This bus partition permits to increase the data throughput.

The ARM-7 microcontroller communicates with the CPU board through a USB-2 bus with a theoretical throughput of $11[Mbits/s]$. It can be used to control the robot's stability using the inertial unit. The operating system is based on Linux, but the whole system can be modified.

B. *Electronic system*

Custom designed integrated circuits based on Microchip 16 bit dsPICs microcontrollers were designed to control the actuators. These circuits are responsible for servo-control, bus control, sensor management, and power converters. Each circuit can drive up to two actuators. Each actuator is equipped with magnetic rotary encoders (MRE) that yield absolute outputs. Figure 12 shows the overall electronic architecture of the system.

One dsPIC based circuit, connected to the ARM7 board through $I2C^{TM}$ bus, is devoted to the signal acquisition from two gyrometers and three accelerometers. Signals issued from accelerometers and gyrometers can be combined to get an acceptable feedback of the robot's trunk orientation [12], [30].

Another dsPIC based circuit manages an infrared transmitter/receiver and a series of LEDS.

For vision purposes the head of NAO houses a CMOS videocamera. It is a 30 FPS camera with a 640x480 resolution. It can be controlled through the $I2C^{TM}$ bus.

The robot is also equipped with two ultrasonic sensors, four FSRs per foot (force sensitive resistors), four microphones, two loudspeakers, Ethernet, serial and USB ports, 1 Gb USB key, WiFi interface through USB-2 bus, and a series of 20 LEDS.

Low level control is updated every millisecond. The high level decision loop can be executed every $20[ms]$. Sensor data is refreshed every cycle of $20[ms]$.

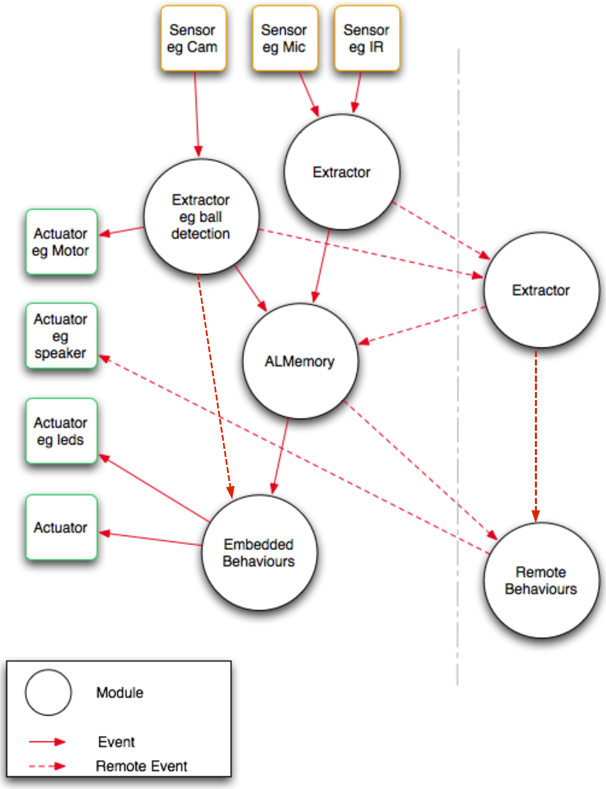

Fig. 13. NaoQi architecture concept.

IV. SOFTWARE ARCHITECTURE

A. *NaoQi distributed architecture*

NaoQi is the Aldebaran Robotics software framework, that is registered for patenting [31]. It is a modular and distributed environment that can deal with a variable number of executable binaries, depending on the user's architectural choices. The architecture is event-driven. Figure 13 illustrates the concept of the NaoQi architecture. A lot of effort was required to make the architecture support both parallel and sequential calling methods. The NaoQi architecture appears to be more user friendly than Corba-based architectures such as *open-hrp* used for HRP-2 [32].

The advantages of a distributed environment are manyfold. It allows the user to run behaviours locally or remotely. Robot functionalities such as motion, vision, text-to-speech, etc., can be run on a robot in the same executable or in a standalone executable that interacts with other modules on other computers. Development is made easier in a distributed environment since the same code can be compiled on different platforms and cross-compiled for embedded execution. A distributed environment also allows the user to look at variables and running methods on any real or simulated robot from the programming interfaces.

The functionalities of NaoQi are listed below.

- Programming in many languages. Users can control the real robot or simulate it with C++, Ruby, or Urbi [33]. Programming in $C\#$, python, Matlab,and Java will be possible in a future version.

- Executing methods through parallel, sequential or event-driven calls.
- Process management. It includes finding a process and running a method in the process tree.
- Modularity. The user can choose whether to compile an application as a dynamic library or as an executable without changing source code.
- Multi-platform framework that supports Linux, Specific linux OS on Geode (AMD processor inside Nao), Windows XP, Windows Vista, and Mac OS X.
- Encapsulation of communication. The user can choose the process or the method to be executed without knowing SOAP or CORBA message passing for example.
- API management to show or hide methods to other applications.
- Shared memory management. Read, write and subscription procedures are available.

There are three main object types in the NaoQi architecture:

- broker: its role is to expose modules to the rest of the architecture. A module must be linked to a broker to be accessible. Brokers manage network communication, and a broker can be defined as a child of another broker, this yields a distributed broker tree.
- module: this contains user defined methods. It can expose methods called "bound methods" to the rest of the system
- proxy: this is designed to call a module wherever it is. The proxy explores the broker tree to discover the module location in the network, then it chooses the most optimised way to communicate with it.

When creating modules, the user instantiates a broker, then links his modules to the broker instance. The module will automatically declare its bound methods. At any time, the user can instantiate a proxy by specifying the desired module name. As soon as the proxy is ready the user can call bound methods without having to consider whether the module is local or remote, or if it is written in ruby, c++ or in any other compatible language. Three modules form the core of the NaoQi system, namely *ALMemory*, *ALLogger*, and *ALPreferences*. They are automatically loaded at boot-up. *ALMemory* enables intra-process or inter-process way to share memory. Aldebaran modules and user modules can add and inspect variables from *ALMemory*. The *ALPreferences* module manages all preferences and initialization XML files. Each module can use *ALPreferences* to read/write attributes, or store them in the *ALMemory* module.

It is important to note that the whole system is thread safe, and that the NaoQi architecture allows dynamic introspection.

B. Device Control Manager (D.C.M.)

The D.C.M. is a NAO real time module that is part of the NaoQi system, and is linked as a library. It is in charge of the communication with the electronic devices of the robot except sound sensors and video-camera. It can be seen as the link between the upper level software composed of other modules, and the lower level software that is embedded inside the electronic boards. The D.C.M. gets information from the electronic devices through the chestboard and also accesses devices located in the head and connected though the $I2C^{TM}$ bus. For example, modules like *Motion* and *Leds* can send commands directly to actuators using the D.C.M., while extractors and other modules use sensor results delivered by the D.C.M. to *ALMemory*. In case of actuators, modules need to send an update request to the D.C.M. using a timed command.

A timed command is an order containing a float number to be sent to a subdevice actuator and the time at which the order should be executed. More than one timed command can be included in the same request. The time is an absolute value in milliseconds based on the system time, and coded as a 4 byte integer. The D.C.M. stores all timed command for each actuator, then at each $20[ms]$ cycle it analyzes the previous and next orders based on the current time and computes the appropriate command to send using a linear interpolation.

The main interests of timed command are:

- There is no need for the upper level to know the D.C.M. update time precisely, and no need of any synchronization mechanism, because precise command times are automatically used by the D.C.M. to send a good evolution of the command to actuators. The only requirement is to send commands in advance.
- As the D.C.M. knows actuators commands in advance, it can send them previously using its own thread, so that there is no delay between two commands from the actuator point of view, even if the module itself is delayed by the system or by the network latency.
- Other modules do not need to be real time. This relaxes contraints on programming.
- A whole choregraphy can be sent to many actuators at the same time. Whatever the communication delay or lags, actuators commands will be sent correctly.
- Synchronizing many actuators from different modules is possible, just by sharing the time.

C. Control using ALMotion module

The motion module, named *ALMotion*, was designed to facilitate the control of NAO, going further than simple joint-space commands to allow direct control of end effectors, or to directly manipulate the center of mass and request high level motions such as *walk 10[cm] straight*. The motion module offers the following options:

- resolve the kinematic model
- control the robot in joint space for direct control of joint angles
- control an end effector in the Cartesian space
- control the torso orientation
- control the COG (center of gravity) position relative to the support foot
- create and control walk primitives.
- control hardware parameters such as joint stiffness
- open-loop stabilizer

Before using inertial and FSR sensor feedback it is necessary to generate robust moves and walking motion in open loop. The control of the COG position relative to the support foot is inspired by the work developed by Sugihara et al [34],

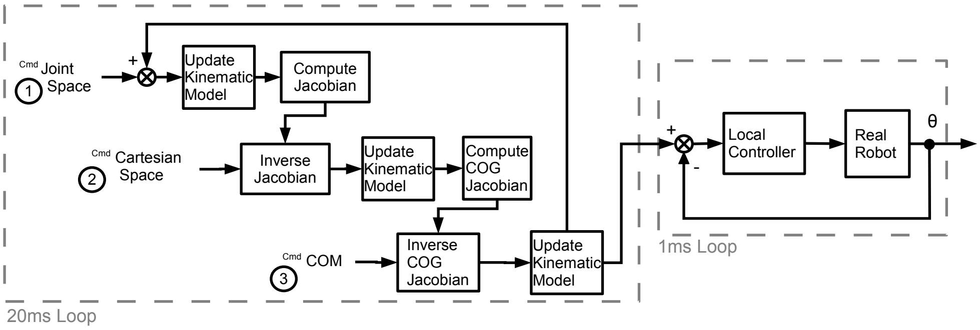

Fig. 14. Algorithm for ALMotion.

who defined the COG Jacobian to generate stable real-timed humanoid motion.

Figure 14 shows a simplified view of the 3 step cascade *ALMotion* algorithm. Each joint, Cartesian or COG command is called a *task*. All tasks are filtered by priority, with the highest priority given to the balancing task (i.e. COG Jacobian) and the lowest priority to joint space commands. Once a task is given control and assigned the resources it needs, it can only be interrupted – and killed – by a higher priority task. For Example, if NAO is in double support mode (i.e. two feet on the ground), all the Cartesian and joint space commands that involve both feet will be ignored by balancing tasks that are active in this case. Before the balancing task, an internal kinematic model of NAO is updated relatively to all other joint and Cartesian tasks. So the COG Jacobian is computed taking into acount all the perturbations on the robot COG involved by these tasks.

Regarding the high level walking *task*, a foot step planner is used to generate the body motion trajectory, the foot swing trajectory – based on a cycloid function – and the joint space arm motions. The planner enables walks to be composed using four walking primitives (straight, turn-in-place, side-step and arc). Figure 15 shows the step parameters for straight forward walking.

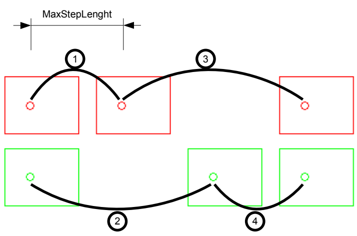

Fig. 15. Step primitives for straight forward walking.

The COG trajectory is generated through a simplified dynamic 3D inverted pendulum model [12]. Due to this simplification and because there is no feedback of real COG, some instability may occur in the robot. Therefore some adjustable parameters were defined. The ZMP (Zero Moment POint) offset in the x-direction describes a positive length starting under the heel position of a footstep, which causes the COG trajectory to linger longer on the supporting foot (see figure 16). The ZMP offset in the y-direction can be used to reduce the width of the COG sideways move.

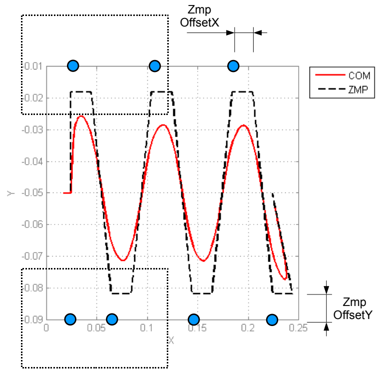

Fig. 16. COG trajectory generated from the adapted ZMP trajectory.

The robot is capable of walking forward and following arc of circle trajectories using the open-loop stabilizer based on the COG Jacobian. The robot does not fall as long as the ground remains flat enough. Future developments aim at incorporating a closed-loop stabilizer to equip the robot with better capabilities of resisting disturbances while walking, that may arise from ground irregularities or collisions. This requires reliable feedback of the real COG and real ZMP.

V. Conclusion

This paper presented the design of the small-size and lightweight humanoid named NAO developed by the French Aldebaran-Robotics company in collaboration with research laboratories. The robot will be for sale on a large scale for laboratories and the public. The designers devised an affordable and performant humanoid. They followed the four following guidelines during the whole process of manufacturing: affordability, performance, modularity and open architecture. NAO presents the following interesting and innovative features:

- the pelvis is made of two coupled hinge joints inclined at 45° driven by a single motor.
- the motorization uses actuator modules that include custom universal joint, custom gear mechanism, MRE sensors, and custom servoboard.

- a special device communication manager deals with data exchange on the bus network.
- the software architecture relies on a open modular and distributed system that is easy to manage and presents a comprehensive set of functionalities to control a legged robot.

A simplified version of NAO was delivered to 16 teams of the standard RoboCup league in 2008. In this version wrists and hands are not actuated. The robot will be tested by international teams as they will prepare and program a set of 3 NAOs to play soccer in this competition. This will bring some positive feedback to improve the robustness and the reliability of the robot.

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