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Mechatronic design of NAO humanoid

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***Abstract*— This article presents the mechatronic 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 existing humanoids 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. 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.**

I. INTRODUCTION

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

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. Current 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). The target price of NAO will be about 10K euros for academics. 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 relative to its height to weight ratio or body mass index (BMI). Table I gives the BMI for different functional humanoid robots. 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. Compared to a heavy robot, a lightweight robot means smaller and less powerful motors, less thermal dissipation, larger acceleration range, and better dynamic capabilities. Due to their reduced weight, lightweight robots are less dangerous and less subject to breakdown.

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

Fig. 1. Aldebaran-Robotics NAO humanoid.

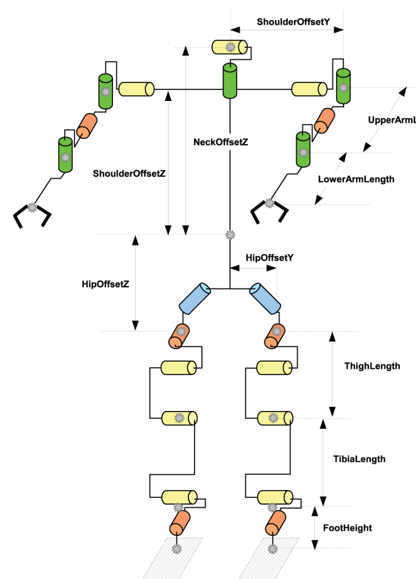

Fig. 2. Detailed kinematics of NAO. Wrist joint not represented.

Biped robots are built by robotics research teams to focus on a particular research subject. One recurrent subject is the development of efficient walking gaits, like in the case of the ETL-humanoid [8], the BIP biped [9], the 2D Rabbit biped [10], or the Johnnie and LOLA humanoid robots [11], [12], [13]. Other subjects concern the design of artificial limbs for disabled people, like the Robian biped [14], or the introduction of natural dynamics through the use of flexible actuators, like the series of robots designed at MIT [15]. All these robots were not devised to be fully autonomous in terms of energy, neither operational. Other

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

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

robots were designed in collaboration between researchers, engineers and manufacturing companies to reach these objectives. 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. The HRP-2 and HRP-3 robot manufactured by Kawada Industries are also advanced technological achievements [4], [5], [6], [7]. HRP-2 can walk up to $2.5[km/h]$, and can lie down and get up again by itself. These Japanese robots can be considered energetically autonomous and capable of achieving a wide range of movements. NAO was designed to perform smooth walking gaits, even when changing speed and direction. The walking speed must be similar to the walking speed of 2 year old children of the same size, that is about $0.6[km/h]$. The performance targets for NAO also include the capability of performing a rich panel of movements with smoothness and precision, and a certain degree of interactive autonomy.

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. Secondly, the modular design of the robot's limbs is also very useful to promote further evolution. The head of NAO 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. Since NAO will be for sale on a large scale, its maintenance must be optimized so that spare parts can be changed quickly.

This paper describes the kinematics, the dimensioning of leg actuators, the modular design of the actuator units and the computer-electronic architectures.

II. KINEMATICS

Table III gives the main characteristics of the NAO humanoid. 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): the horizontal axis rotary joint at the waist and the rotary joints of vertical axis for each leg hip. The coupling of the pelvis joints prevents the trunk from rotating along the vertical axis (yaw rotation) when both legs are in support, but this is not a problem for walking and other motion behaviors. The proposed mechanism presents several advantages. Only one motor is required to drive the pelvis instead of three in the classical design, this allows to reduce building cost and to save space in the lower part of the trunk. In addition, this structure helps to better distribute the power between the hip roll joint and the pelvis joint, and confers a specific motion style to the NAO humanoid. Unlike prototypes such as H7 [17], Wabian-2R [18] 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 [19].

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.

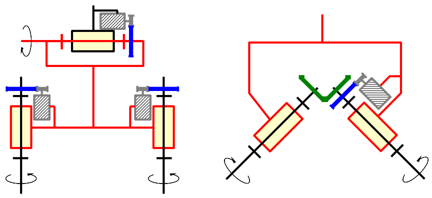

Fig. 3. Left-hand side: classical set of three rotary joints, one horizontal axis rotary joint at the waist and two vertical axis rotary joints for the legs. Right-hand side: coupled inclined axis rotary joints for the NAO pelvis.

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

III. DIMENSIONING OF LEG ACTUATORS

Some humanoid designers developed an iterative process for the mechanical design and ran 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, $1[sec]$
2) standing up from flexed knee position, $1[sec]$,
3) leg transfer during walking step, body motionless, $1/3[sec]$
4) body translation in the direction of motion during leg stance, $1/3[sec]$
5) body sinusoidal movement in the direction of motion during leg stance, $1/3[sec]$ (fig. 4),
6) simultaneous knee flexion and body forward bending for pick up, $1.2[sec]$ (fig. 4).

For basic movements 3 and 4, the target walking velocity can be taken into account by changing the duration of the movement.

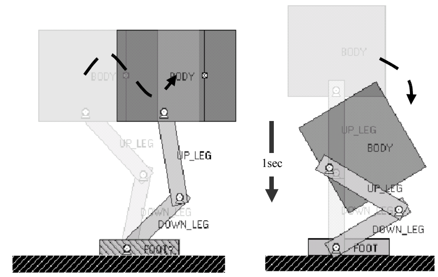

Fig. 4. Sagittal plane simulation experiments of body sine move and pick up.

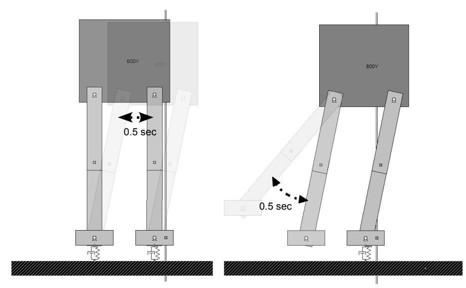

Fig. 5. Frontal plane simulation experiments of sideways move and leg lift-off in lopsided position.

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

1) lopsided move on both legs, $0.5[sec]$ (fig. 5),
2) leg lift off in lopsided position , $0.5[sec]$ (fig. 5),

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 6 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.

The rpm versus torque specifications of off-the-shelf motors were compared with the desired variations to select the best suited motors thanks to a custom designed and interactive graphical interface. Figure 7 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.

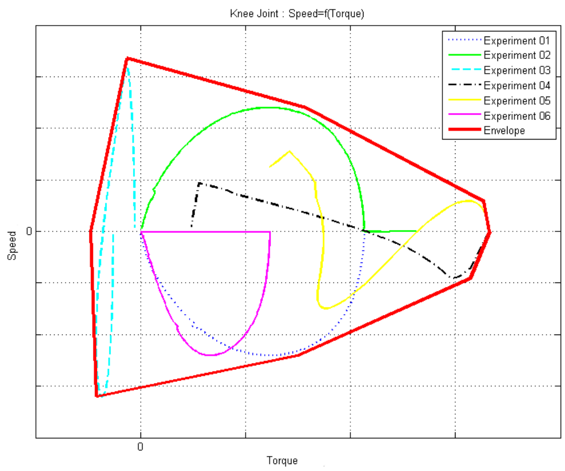

Fig. 6. Speed versus torque of knee actuator relative to experiments 1 to 6 in the sagittal plane.

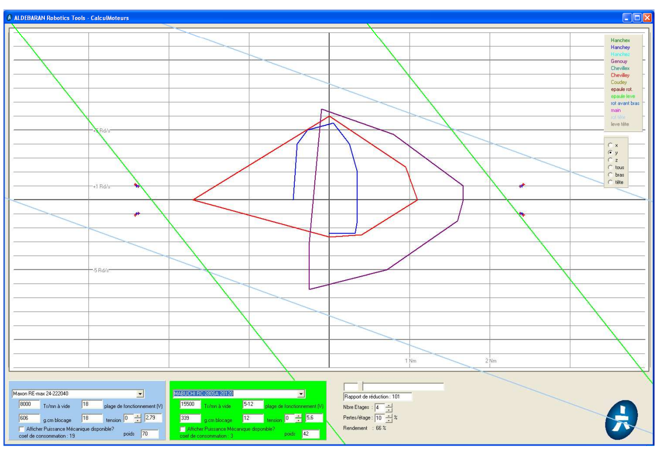

Fig. 7. Software used to choose motor and reduction ratio for the hip, knee and ankle pitch actuators.

In the process of dimensioning it is interesting to check the load to motor inertia ratio k.

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

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 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,

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

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.

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

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

IV. MODULAR ACTUATOR UNIT DESIGN

Modularity was also the concern of designers of the LOLA bipeds [13] or the QRIO humanoid [16].

Off-the-shelf RC servomotor modules were used for the design of most humanoid robots of the kid-size league of RoboCup. Despite of good performance for some of them, RC servos were not selected for NAO because the packaging is generally not suited and bulky, and the gear reduction mechanism and the joint control system are fixed and cannot be adapted.

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. [20] 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 [16], 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. In the case of NAO the response time must be less than $6[ms]$. This value was obtained from specifications of joint maximal angular velocity and maximal angular deviation at the ankle for motions that involve one leg in support.

Off-the-shelf motors for legged robots do not exist. Humanoid designers often use existing brush DC motor [4],

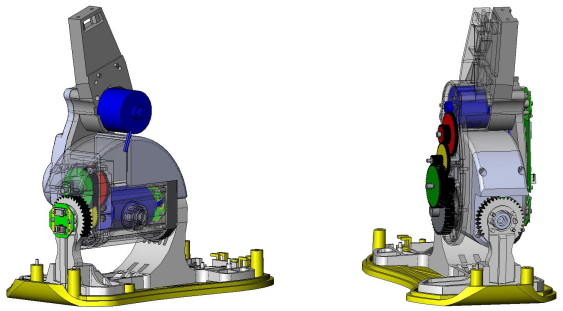

Fig. 8. CAO design of ankle module. There is a double supporting structure for the pitch joint. The half of this structure is represented in transparency in the right hand-side figure but is not represented in the left-hand side figure.

TABLE V

ACTUATOR 1 SPECIFICATIONS, MOTOR (M) AND REDUCTION (R)

Characteristics	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*

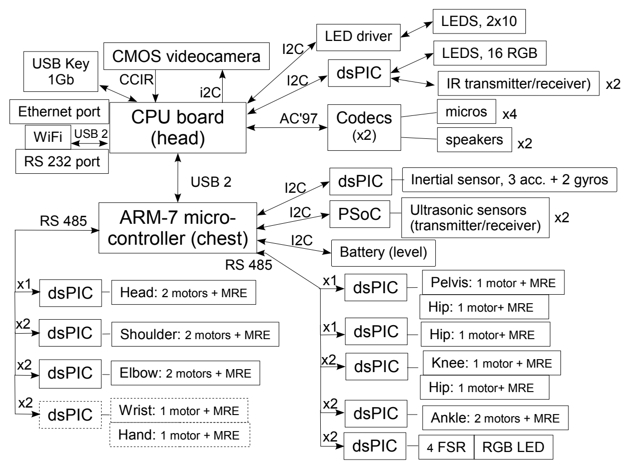

Fig. 9. Electronic architecture of NAO. MRE stands for magnetic rotary encoder.

[5], [11], brushless DC motor [13], or proprietary motors [20]. 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 [16] and can therefore be more sensitive to shocks. 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 [21]. 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.

Thanks to the dimensioning study the number of actuators was reduced to 4 for all the joints, with two kinds of motor (M1, M2), and two types of reduction gear (R11, R12) (see table IV). The innovation brought to the design of the NAO actuators consisted of 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. Tables V give the technical data for these actuators. Figure 8 gives a CAO view of the ankle joints module.

V. 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 the 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 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.

VI. ELECTRONICS

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 9 shows the overall electronic architecture of the system. Table II gives the list of sensors that equip NAO. One dsPIC based circuit, connected to the ARM7 board through I2C™ 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 [22], [12]. Another dsPIC based circuit manages an infrared transmitter/receiver and a series of LEDS.

VII. RESULTS

The first operational prototype of NAO was capable of reaching a forward walking velocity of $0.36[km/h]$ with an open-loop walking algorithm that did not take into account the inertial system feedback (see video). This velocity is half the velocity that was specified for the design –$0.6[km/h]$, but the robot is expected to reach such a target velocity thanks to the design of closed loop control. The robot is capable of making turns showing a specific style due to the pelvis kinematics (see video). The algorithm was based on a ZMP cascading procedure inspired from [23].

VIII. 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 with objectives of affordability and performance. 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.

The main advantages of NAO are its light weight and its affordability compared to other existing robots of similar performance. The maintenance required for this robot is easy and not excessive. The architecture of control and the software are customizable. The robot also comes with a rich environment of development.

A specific version of NAO was delivered to 16 teams of the standard RoboCup league in 2008 to play soccer. This brought very positive feedback to improve the robustness and the reliability of the robot.

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