

Simulating CALUMA (CASSINO Low-cost hUMANoid) robot carrying a load

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Nestor Eduardo Nava Rodriguez, Giuseppe Carbone and
Marco Ceccarelli

*LARM: Laboratory of Robotics and Mechatronics, DiMSAT – University of Cassino, Via Di Biasio 43-03043
Cassino (Fr), Italy*

Abstract: In this paper, the operation of CALUMA (CASSINO Low-cost hUMANoid) robot has been investigated for a task while carrying a load. CALUMA robot is the result of a design project that has been elaborated for designing and building a low-cost easy-operation humanoid robot by summarizing experiences and prototypes that have been developed at LARM. Dynamic simulations have been computed by using ADAMS software in order to study dynamical aspects of CALUMA operation while carrying a load. The dynamic simulations have also been used for studying the manipulation performance of CALUMA robot. Simulations have given results that confirm the feasibility of the proposed design, as shown in the reported examples.

Key words: Robotics, humanoid robots, low-cost robots, dynamics, simulation.

INTRODUCTION

Science fiction has fields of robotics with visions of technology far beyond the contemporary state of the art. The term *robot* was coined by Czech author Capek in his 1924 production of *Rossum's Universal Robots*, as illustrated in Ambrose (2006). The robots were played by human actors and dealt with the issues of slavery and subjugation. They were the first ideas of modern humanoid robots (Ceccarelli 2001).

In 1972 professor Ichiro Kato of Waseda University presented WABOT-1 as the first humanoid robot beyond of science fiction (Kato and Tsuiki 1972). Many research activities are currently carried out in humanoid labs in Japan, Korea, United States and Europe. Examples of humanoid robots that have been developed in Japan are WABIAN-II of Waseda University (Ogura *et al.* 2006), the ballroom dance robot of Nomura Unison Co. (Hassler 2005) and HRP-2 of AIST (Hirukawa *et al.* 2004). The humanoid robots DB (Ude *et al.* 2001), H10 (Hackel *et al.* 2003), CENTRAUR and KHR-1 (Kim and Oh 2003) are

examples of robots that have been developed in United States, Europe and Korea, respectively. Other significant humanoid projects are reported in Android (2006).

Humanoid robots are machines with complex systems. Their structure requires high costs and operating their control systems requires high-level skills. One feasible alternative solution to these problems can be proposed through the development of low-cost humanoid robots, as discussed, for example, in Carbone *et al.* (2001). A low-cost humanoid robot should be conceived with the aim of designing it by using industrial components that have a robust and simple mechanical design, are easy to operate with flexible easy programming and are inexpensive both in design and operation. Those goals can be achieved in a very practical way by using low-cost components from the market into a suitable design for a whole humanoid robot system. Then, the mechanical design of mechanism architectures can be conceived in such a way that links and transmissions are easy to manufacture and assemble. Nevertheless, such a low-cost design will yield to a humanoid robot with limited capability both in mechanical versatility and programming flexibility. But in general, it can be thought that a low-cost humanoid robot can have still basic performances for mobility, manipulation and autonomous operation that are useful in many applications.

Humanoid robots can be developed to perform human tasks in dirty or dangerous jobs, or personal assistance to assist sick and elderly people. Moreover, a humanoid robot is able to manipulate objects of a wide variety of sizes, shapes and frictional properties. As for research activity

Corresponding Author:

Nestor Eduardo Nava Rodriguez
LARM: Laboratory of Robotics and Mechatronics
DiMSAT – University of Cassino
Via Di Biasio 43-03043 Cassino (Fr), Italy
Tel: 0039-0776-2993388; Fax: 0039-0776-2993711
Email: nava@unicas.it

Table 1 Mobility ranges of the CALUMA active joints in Figure 1.

Joint	Mobility
Leg (°)	0 to 360
Trunk (°)	-40 to 40
Shoulder (yaw) (°)	-90 to 90
Shoulder (pitch) (°)	0 to 360
Neck (mm)	0 to 90
Head (°)	-90 to 90
Finger (°)	0 to 54
Elbow (°)	-90 to 90
Wrist (°)	0 to 360

on manipulation by humanoid robots, studies have been developed on the dynamic balance of a humanoid robot while grasping objects, as reported in Harada *et al.* (2004).

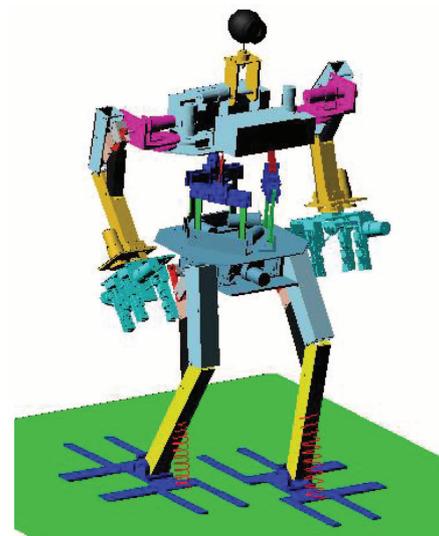
The aim of this paper is to illustrate simulation results of CALUMA (CAssino Low-cost hUMANoid robot) operation while carrying a load. CALUMA is a low-cost easy-operation robot that has been conceived at LARM in Cassino within humanoid research activity, as illustrated in Carbone *et al.* (2001) and Nava *et al.* (2005, 2006a–c). Previous simulation of CALUMA walking has been elaborated in the recent past with successful results, as reported in Nava *et al.* (2006a,b). In the present work successful simulations of CALUMA walking movement while carrying a load have been obtained with suitable results for the robot parameters.

CALUMA ROBOT

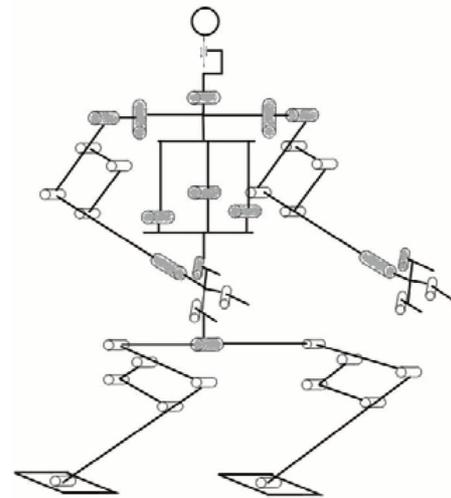
CALUMA robot is a new low-cost humanoid robot that is under development at LARM of University of Cassino. Figure 1 shows a design architecture for this robot. In particular, Figure 1(a) shows a 3D model of CALUMA and Figure 1(b) shows a kinematic scheme with actuating joints for each robot module. This robot has a total of 14 active degrees of freedom (DOFs): one is for pitch motion of both legs; one is for pitch motion of each arm; one is for yaw motion of each shoulder; one is for roll motion of each wrist; three are for trunk motion (pitch, roll and yaw); one is for pitch motion of neck; one is for up–down motion of head; and one is for the opening–closing motion of each hand, as shown in the scheme of Figure 1(b). Table 1 lists mobility ranges of the active joints in CALUMA.

The maximum dimensions for the CALUMA design of Figure 1 are 962 mm height, 839 mm width and 413 mm depth. Basically, this robot is composed of leg, arm, head, trunk and hand sub-systems that have been designed and built at LARM in Cassino in the last decade as previous specific experiences.

The design of these sub-systems has been adjusted in order to obtain a whole assembly of a humanoid robot, as reported in Figure 1(a) (Nava *et al.* 2005). A design goal has also been to obtain mechanisms that can be easily man-



(a)



(b)

Figure 1 Design architecture for CALUMA robot: (a) a 3D model; (b) a kinematic scheme (active joints are drawn in grey).

ufactured and assembled with actuators and components that are available from the market.

In particular, in the leg design, CALUMA robot uses a Chebychev-Pantograph mechanism in order to transmit the movement to the feet, as illustrated in Ottaviano *et al.* (2004). The driving-leg mechanism for CALUMA has been modified in order to obtain a suitable mechanism that generates dynamically balanced walking performance of the robot. The same driving mechanism has been implemented in arm sub-systems, as shown in Figure 1(b). In fact, this mechanism can also perform a convenient movement for the arm module operation.

The parallel manipulator CaPaMan2bis (Carbone and Ceccarelli 2005) has been adapted for the trunk sub-system of the CALUMA robot. The modifications of

CaPaMan2bis with respect to the original prototype can be recognized in the shape of the movable plate in order to properly install the head, arm sub-systems and commercial PLCs that are part of the control system.

The head module is a telescopic manipulator with 2 DOFs, as illustrated in Carbone *et al.* (2003). The head module uses a commercial low-cost Web-cam for a visual interface between the robot and the environment.

The hand module is a three-fingered hand prototype with only one motor for actuating all the fingers. This prototype is a simplified version of LARM Hand, Nava *et al.* (2004). The hand sub-system uses a belt mechanism to reduce the number of actuators to the cited only one.

The above-mentioned modifications for CALUMA modules have been elaborated as part of the design process for a low-cost humanoid robot. A first proposed structure has been presented in Nava *et al.* (2006a). After some suitable changes due to additional design considerations and simulation results, a second structure has been proposed in Nava *et al.* (2006b). The robot structure of Figure 1 is the last structure that has been obtained as a result of the design evolution after further design considerations and simulation results.

The robot sub-systems require torque and power densities that can be achieved by lightweight direct current (DC) motors and geared speed reducers. The actuation for CALUMA is proposed with DC brushless motors that provide the highest torque densities for electromechanical systems with robust and compact design. The mechanical design of the leg, arm and hand modules is based on linkage mechanisms for driving the movement. For such mechanisms, these sub-system motions can be performed by using DC motors. In the trunk module, each limb mechanism can be actuated by a DC motor connected directly to the input crankshaft. The 2 DOFs of the head module can be actuated by using a DC linear actuator for the up-down movement and an additional DC motor is needed for the neck movement. Those DC actuators can be controlled conveniently by using a low-cost easy-operation commercial PLC.

SIMULATION OF CALUMA CARRYING A LOAD

A dynamic simulation of CALUMA operation while carrying an object has been developed in an ADAMS environment in order to study task performance. MSC software ADAMS has been used for dynamic simulations owing to its convenient features in simulating the dynamics of multi-body systems. The MSC.ADAMS[®] can obtain realistic simulations of full-motion behaviour for complex mechanical systems, as outlined in MSC.ADAMS (2005). Previous simulations of CALUMA walking movement have been carried out with satisfactory results, as reported in Nava *et al.* (2006a–c).

The dynamic simulations have been carried out by using a PC with processor Pentium(R) 4, CPU 2.60 GHz and 1.00 GB of RAM. The simulation has been applied for an

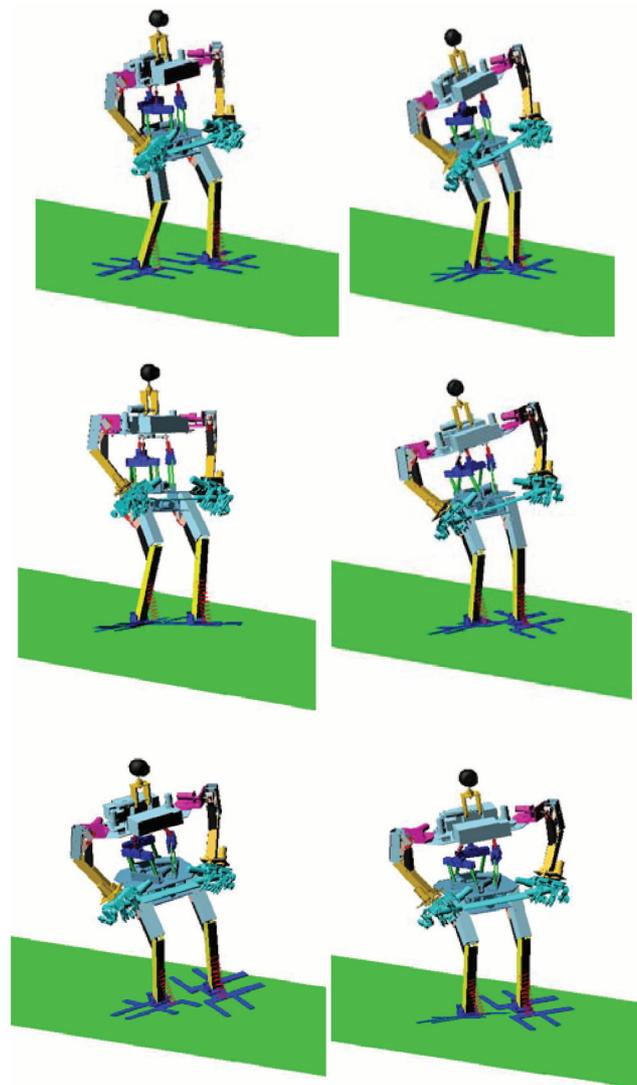


Figure 2 A sequence of CALUMA walking while carrying an object as simulated in ADAMS environment.

operation of CALUMA that walks for 6 s. The computer processing time for calculations has been about 90 min by using 100 computation steps in 1 s as time intervals for calculations by the integrator GSTIFF integrator of ADAMS (MSC.ADAMS 2005).

Figure 2 shows a sequence of the walking operation of CALUMA carrying an object by using the robot model of Figure 1(a). The simulation of Figure 2 consists of several steps of CALUMA while carrying an object.

Table 2 lists the main dynamic characteristics of the robot components for the proposed ADAMS model.

External forces, gravity, contact constraints and friction and inertia properties have been considered in the ADAMS environment for simulating the CALUMA operation. A grasped object has been considered to have 1.5 kg weight, 30 mm of height, 60 mm of depth and 450 mm of width. In addition, friction coefficients at CALUMA joints have been assumed as equal to 0.5 for static configurations and equal to 0.3 for dynamic operations.

Table 2 Principal inertia data for CALUMA modules.

Sub-system	Weight (N)	I_{xx} (kg m ²)	I_{yy} (kg m ²)	I_{zz} (kg m ²)
Leg	23.09	2.29E-2	1.79E-2	5.62E-3
Trunk	161.98	0.18	0.11	9.55E-2
Head	7.1	0.57E-3	0.50E-3	3.78E-4
Arm	12.42	2.63E-3	2.51E-3	5.39E-4
Hand	7.24	2.82E-3	2.42E-3	6.90E-4
Total	254.58	0.24	0.16	0.11

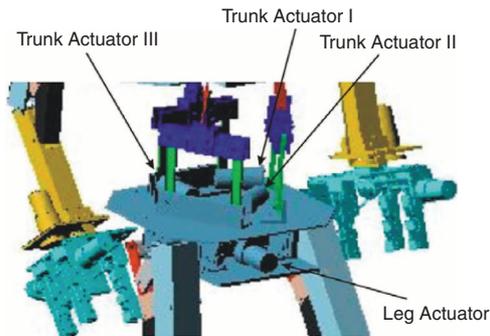


Figure 3 Actuating joints of CALUMA during the simulation of walking while carrying a load.

The contact between CALUMA feet and floor has been elaborated by using the Contact Force Tool of ADAMS (MCS.ADAMS 2005), in which the contact is modelled as a contact force between solid bodies. In particular, the friction effects at the contact location have been modelled by using a coulomb friction model. In the ADAMS simulation, static and dynamic coefficients of friction between the CALUMA feet and floor have been assumed as equal to 0.7 for static conditions and 0.5 for dynamic conditions. In this ADAMS sub-routine tool, the contact is modelled as a non-linear spring damper between the bodies and the force contact is computed consequently.

In the simulated manipulation task, only four DOFs of CALUMA are active during the operation. In particular, only leg actuators and trunk module actuators are operated during the dynamic simulations. Figure 3 shows the nomenclature that has been used for the operating joints. Figure 4 shows the input plots for the actuating DOFs that have been used for the simulation. In particular, Figure 4(a) shows the input for leg actuators; Figure 4(b) shows the inputs for trunk actuators I and II; and Figure 4(c) shows the input for trunk actuator III. The input for leg actuators is a time quasi-constant rotation of the crank. The trunk actuators I and II have the same input movement between 0° and 20° but with different direction. The trunk actuator III has a rotation movement from -20° to 20°. The limbs of the parallel manipulator are located in a configuration of 120° between them. Thus, limb III operates in a plane that is orthogonal to the walking direction, and limbs I and II are symmetrically located with respect to that direction, as shown in Figure 1. The inputs of the trunk actuators have been designed after several preliminary simulations. The

input motion of trunk in Figures 4(b)–(d) permits to the trunk sub-system the necessary movement to equilibrate the CALUMA structure during walking with a grasped object.

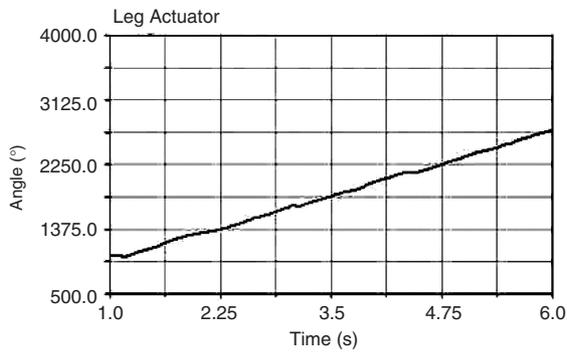
The dynamic simulation has been developed by considering balance strategies that maintain the centre of mass of CALUMA in an area with zero-moment point conditions (Vukobratovic *et al.* 1975). A method for generating the walking movement has been elaborated as based on replicating a human walking. It consists of a synchronization among legs and arms so that when the left arm and right leg move forward, the right arm and left leg move backward. The low number of CALUMA active DOFs for this simulation mode limits the balance capability of robot since the arm movement is necessary for the equilibrium of the structure, as illustrated in Nava *et al.* (2006a, b). Since during the walking of CALUMA while carrying a load the arm sub-systems do not move, the trunk sub-system has to give a major contribution for the robot balance. A contribution of the arm for robot stability can be still recognized in the case when the arms are occupied with the grasped object since their inertia contribute in having pendulum-like reactions due to the trunk motion.

CALUMA presents a suitable behavior while carrying a load during walking as shown through the computed actuator capabilities in Figure 2 and in the plots of Figures 5 to 12.

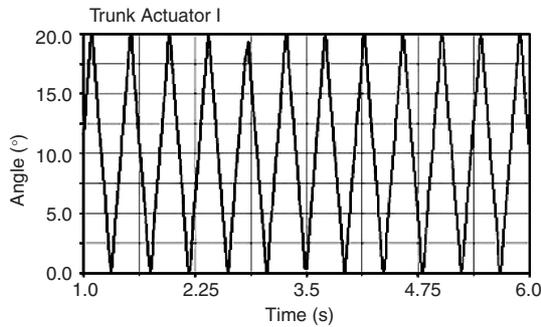
The dynamic simulation of Figure 2 has been developed for a walking of 12 steps of CALUMA with a velocity of 0.5 step/s in a flat terrain. The size of the CALUMA step is about 0.3 m, and CALUMA has walked 3.6 m during the computed simulation.

RESULTS OF DYNAMIC SIMULATION

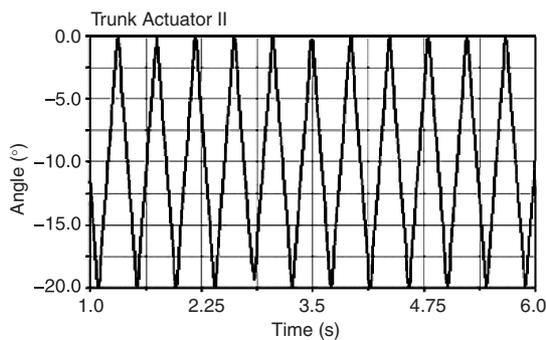
Figures 5 to 12 show numerical results of the simulation of CALUMA operating the sequence in Figure 2. These results are significant information of the robot since they permit us to understand the behavior of the structure. In ADAMS code, reaction forces and motion characteristics can be evaluated for all the joints and any additional points of interest in the structure of the multi-body systems. However, for practical and analysis purposes, an evaluation of simulation results can be limited to few significant plots as reported in the following. In particular, Figure 5(a) shows the angular velocity and torque on the input shaft in leg



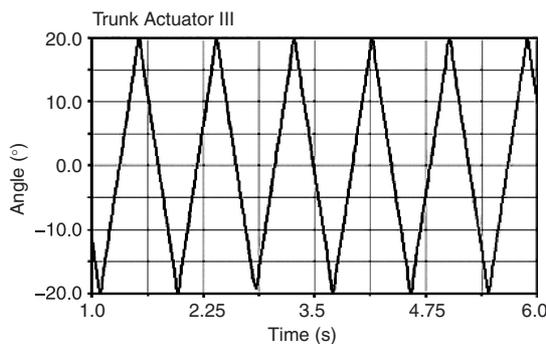
(a)



(b)

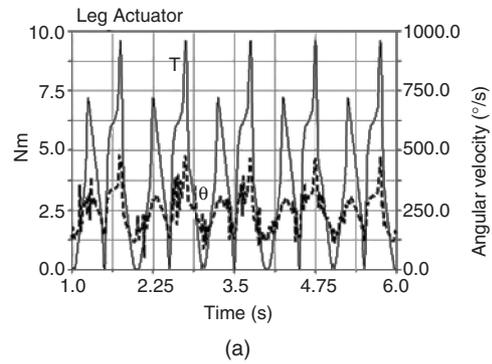


(c)

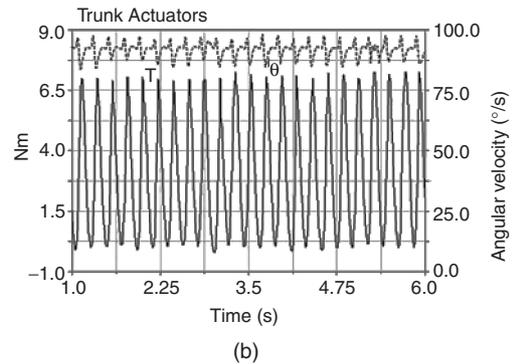


(d)

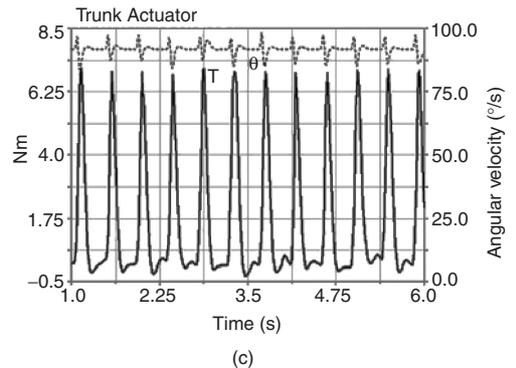
Figure 4 Inputs of the actuating DOFs of CALUMA robot during the simulation of Figure 2: (a) leg actuator; (b) trunk actuator I; (c) trunk actuator II; (d) trunk actuator III.



(a)



(b)



(c)

Figure 5 Results of actuating joints of CALUMA during the simulation of Figure 2: (a) torque and angular velocity of leg actuator; (b) torque and angular velocity of trunk actuators I and II; (c) torque and angular velocity of trunk actuator III.

module; Figure 5(b) shows the angular velocity and torque on the trunk actuators I and II; and Figure 5(c) shows the angular velocity and torque on the trunk actuator III. In these figures the torque is plotted as a continuous line and the angular velocity is plotted as a dotted line.

The plot results of Figure 5 show values of torque and angular velocity that can be suitable for practical implementation.

In fact, the maximum value of actuating torque has been calculated as about 9 N m for the input shaft of legs, as shown in Figure 5(a). Similarly, the maximum value of angular velocity has been calculated as about 400°/s for the leg actuator. The smooth shapes and ranges of result plots can be considered reasonable and feasible for the proposed action since they can be achieved by means of

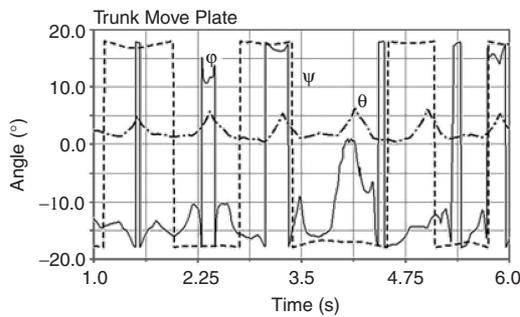


Figure 6 Plots of the orientation angles of the movable plate of trunk sub-system during the simulation of Figure 2.

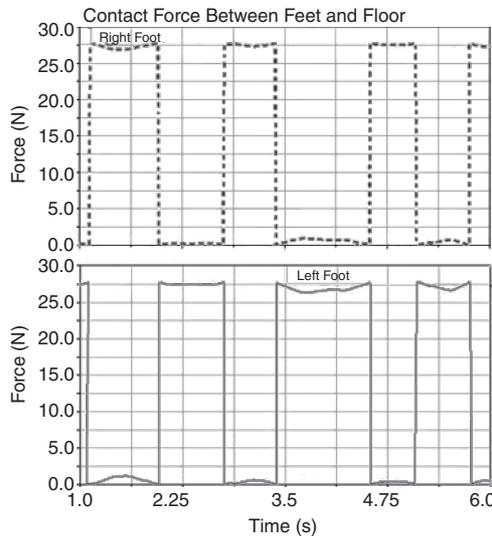


Figure 7 Plots of reaction forces between CALUMA feet and floor.

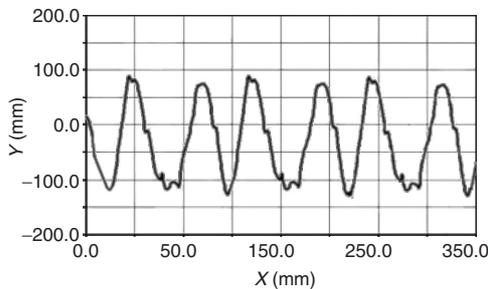


Figure 8 Location of the ZMP of CALUMA during the walking simulation of Figure 2.

commercial DC motors. For example, in the result plot of Figure 5(a), the maximum torque for the actuator is 9 N m and the maximum angular velocity is 400°/s. The commercial DC motor Crouzet 80831007 (Crouzet 2006), can provide a maximum torque of 10 N m at a speed of 500 rpm that fulfils the requirements for the CALUMA leg operation in Figure 5(a).

Similar considerations can be outlined for the actuators of the trunk for which a maximum torque of about 7 N m

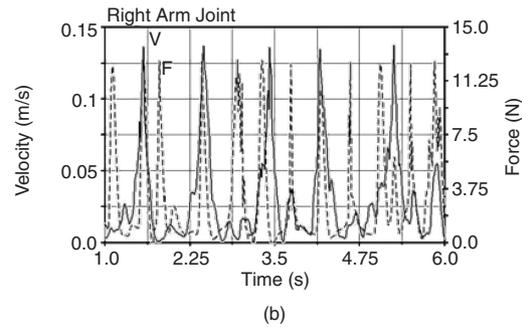
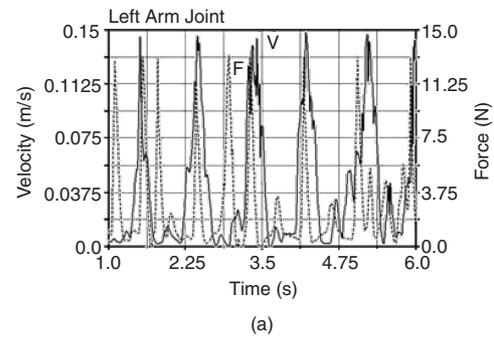


Figure 9 Results of ADAMS simulation of the CALUMA walking while carrying a load in terms of force and velocity: (a) left arm joint; (b) right arm joint.

and a maximum angular velocity of about 90°/s can be used to choose proper DC commercial actuators.

Figure 6 shows the Euler orientation angles of the movable plate of trunk module during the simulated motion of Figure 2. The ψ angle is plotted as a dashed line, θ angle is plotted as a dotted-dashed line and the φ angle is plotted as a continuous line. While the arms are busy with a grasped object, the contribution of arms for the balance of the structure is not available and the trunk sub-system gives a major contribution. Therefore, the trunk sub-system increases its alternating movement with respect to the walking simulation as a need for equilibrating the robot structure. In Figure 6, angles ψ and φ show larger magnitudes than angle θ .

Thus, the trunk sub-system rotates its movable plate mainly about the frontal and lateral axes. This type of movement for the trunk movable plate can help in providing both frontal and sagittal stability to CALUMA. It is worth noting that the plots of Euler angles for the movable plate in Figure 6 show a repetitive cycle. The angle plot of θ shows the fastest motion of the orientation angles even if with lowest magnitude. A lateral movement is mainly generated by the rotation of the moving plate of the trunk sub-system about the frontal axis that is described by angle ψ . The time history of angle ψ illustrates the performance of this lateral motion.

Figure 7 shows the reaction forces between CALUMA feet and floor. In particular, the reaction force between right foot and floor is represented as a dashed line and the reaction force between left foot and floor is represented

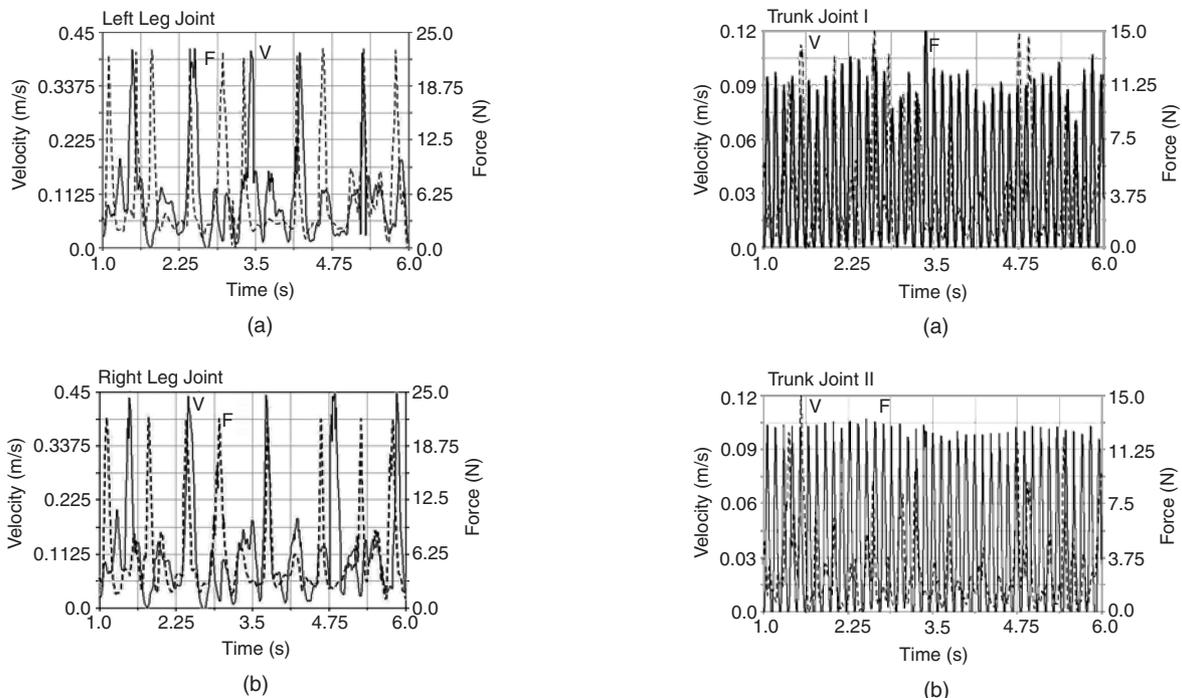


Figure 10 Results of ADAMS simulation of the CALUMA walking while carrying a load in terms of force and velocity: (a) left leg joint; (b) right leg joint.

as a continuous line. By referring to Figure 7, both contact forces have ranges of magnitudes between about 0 and 27.5 N with a function response with a square shape. When a CALUMA foot is in contact with the floor, quasi-constant reaction forces of about 27.5 N are generated during about 1 s. At the same time, the other CALUMA foot is going upward and forward. During this movement, the front part of each CALUMA foot still touches the floor as a characteristic of the CALUMA walking with a certain sliding contact. Thus, in Figure 7 the force is near to zero during this face of the step. The characteristic walking of CALUMA can be identified with a certain/sliding of the foot during its no-active phase. This has been designed as due to mechanism transmission operation to achieve a secure configuration with the foot always near to the floor.

In Figure 8, the efficiency of the simulated walking can be synthetically appreciated by looking at the locations of ZMP in a smooth path within a foot support area that is in the floor plane with a size of 560×650 mm.

Figures 9 to 12 show result plots of force for some representative joints of CALUMA structure in a dashed line and velocity in a continuous line. It is worth noting that Figures 9 to 12 show regular and repetitive cycles of angular velocity and reaction force of CALUMA joints during the simulated operation as characteristics that can be considered suitable for a practical implementation of commercial DC actuators.

In fact, the maximum value of force at the arm joint is calculated as about 12 N and the maximum value of velocity is calculated as about 0.15 m/s, as shown in Figure 9. The

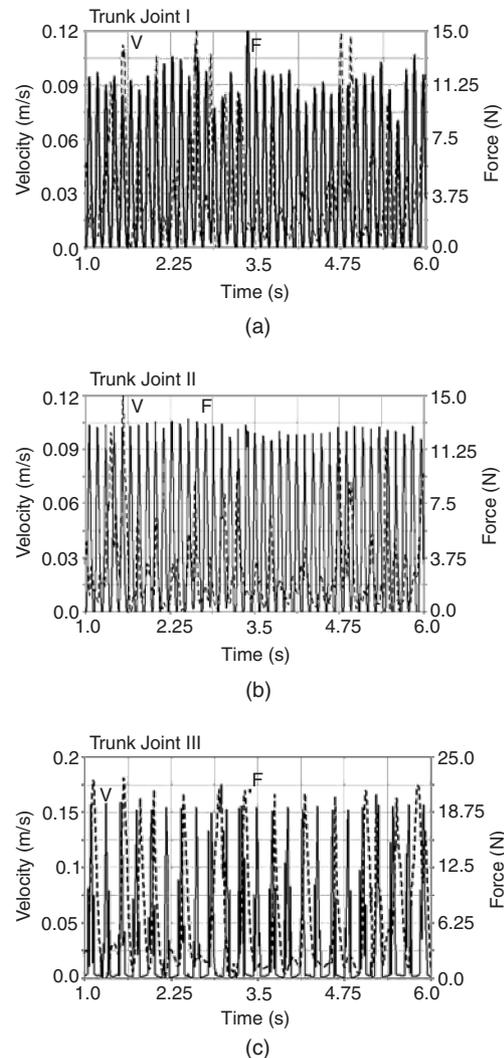


Figure 11 Results of ADAMS simulation of the CALUMA walking while carrying a load in terms of force and velocity: (a) trunk I joint; (b) trunk II joint; (c) trunk III joint.

maximum value of force at leg joints is calculated as about 22 N and the maximum value of velocity for the leg joint is calculated as about 0.45 m/s, as shown in Figure 10. The maximum value of force at trunk joints is calculated as about 22 N and the maximum value of velocity is calculated as about 0.18 m/s, as shown in Figure 11. The value of force at the neck joint is calculated as about 4.3 N, and the maximum value of velocity is calculated as about 0.07 m/s, as shown in Figure 12.

Summarizing, the smooth shapes and limited ranges of the result plots can be considered reasonable for the proposed action of CALUMA robot through commercial actuators. The result plots of the operation of components and joints during the studied walking mode of CALUMA show values that validate the feasibility of the proposed low-cost easy-operation system for a humanoid robot that can carry out manipulation tasks, as reported by the maximum values of the result plots.

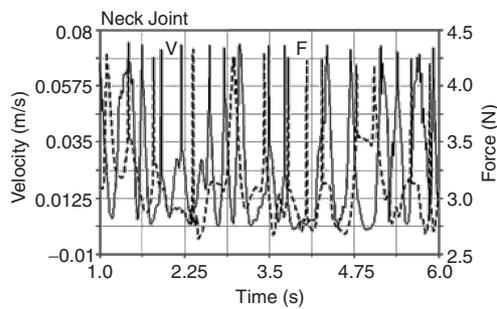


Figure 12 Results of neck joint during ADAMS simulation of the CALUMA walking while carrying a load in terms of force and velocity.

CONCLUSIONS

The load-carrying operation of a CALUMA robot has been illustrated with feasible characteristics through simulation results. A dynamic simulation has been elaborated in ADAMS environment in order to check the performance of the robot in this specific operation. The dynamic simulations have given suitable results with smooth shapes of suitable responses in agreement with low-cost easy-operation design of the CALUMA robot. Numerical results of simulations have validated successfully the operation of CALUMA robot walking while carrying a load as a practical implementation of the proposed design and operation.

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