Dynamics of a Humanoid Robot with Parallel Architectures

Matteo Russo[1] and Marco Ceccarelli[2]

[1] LARM: Laboratory of Robotics and Mechatronics
University of Cassino and Southern Latium, Via G. di Biasio 43, 03043 Cassino, Italy
matteo.russo@unicas.it; marco.ceccarelli@unicas.it

Abstract. This paper describes a modular approach to formulate a dynamic model for LARMbot 2, a humanoid robot that is designed as based on parallel architectures. First, the main advantages and issues of parallel architectures in humanoid robots are briefly analyzed. Then, the mechanical design of LARMbot 2 is described with its modules, namely legs, arms, torso and head. An analysis of its degrees of freedom is reported, and the center-of-gravity Jacobian is evaluated for each module by using its kinematics. Finally, the result is used to formulate the equation of motion of LARMbot 2, in order to obtain walking balance of the robot by coordinating the motion of all the modules.

Keywords: Robotics, Humanoid robots, Parallel mechanisms, Dynamics.

1 Humanoid Robots

The idea of a machine that looks and acts like a human is several millennia old, with the oldest reference in Homer's Iliad (approx. 750 B.C.). In the 20th century, the concept of artificial person developed with the rise of science fiction [1-3]. The first real anthropomorphic robot, WABOT-1, was built at Waseda University, Tokyo, as part of the WABOT project (1970). The same research group later built WABOT-2 (1984) and WABIAN (1997), both biped humanoid robots, and they are still active in the field [3-4]. Around 1986, Honda started to develop a biped platform that underwent through several stages, called "E" (1986-1993) and "P" (1993-1997) series, and led to the creation of ASIMO [5]. ASIMO was officially unveiled in 2000 and had a significant impact on the media all around the world, as a humanoid platform with an advanced vision and navigation system. In 2008, Aldebaran Robotics launched Nao, a programmable humanoid robot that is now the standard platform for several robotics competitions, such as the RoboCup Standard Platform League [6]. In 2013, Boston Dynamics announced the Atlas robot, a biped robot capable of complex dynamic tasks, such as running, moving on snow, performing a backflip, balancing after being hit by projectiles or jumping on one leg [7]. The iCub robot, instead, was conceived as platform for research on cognitive development [8].

Some other examples of humanoid robots are WALK-MAN, a rescue robot developed for unstructured environments [9]; Pepper, manufactured by SoftBank Robotics

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and focused on human-robot interaction [10]; WABIAN-2, one of the most recent humanoids at Waseda University [3, 11]; Ami, a humanoid robot for applications in domotics [12]; REEM-B by PAL-Robotics, designed to help humans in daily tasks [13]; ARMAR, another collaborative robot for home automatization [14-15].

The main challenge of humanoid robot operation is keeping the system balanced during operation. The theoretical basis for robot balancing was set in 1968, when Vukobratovi´c and Juriˇci´c introduced the concept of Zero-Moment-Point, even if the first application was only in 1984, at Kato's laboratory at Waseda University [16]. In the following thirty years, most of the humanoid robots used this concept for the balancing, as shown, for example, in [17-20]. In [21], a flexible approach for the control of robots with various kinematic structures is introduced as based on the center-of-gravity (COG) Jacobian, which allows for the balancing as whole-body compensation of disturbances. Furthermore, as shown in [22], the COG Jacobian can be used also for an easy formulation of robot dynamics with a link-by link approach, which is applied to LARMbot design in this paper.

2 Parallel Designs in Humanoid Robotics

All the designs that were presented in the previous section are characterized by extremely complex control system, and most of the research work is still focused on the control, while the mechanical design of these robots has always been based on serial mechanisms. Very few research groups tried to implement parallel architectures in humanoid robots, because of their limited workspace. However, their high accuracy and payload makes them interesting for humanoid robotics. Most of these groups only focused on the locomotion system by proposing biped legs with parallel design.

The first one was the ParaWalker robot, developed at Tokyo Institute of Technology in 1992, while the Waseda Leg (WL) WL-15 was built in 2001 at the Takanishi laboratory of Waseda University, followed by the WL-16 and the WL-16R series from 2002 to 2007 [23-24]. The last version of the Waseda Leg is the WL-16RV. The LARM biped locomotor [25] was designed as a low-cost, user-oriented leg for a service humanoid robot. The main drawback for most of these legs, however, is the small dimension of their workspace, which allows for a very small step size. For example, the LARM biped locomotor has a a step length to leg height ratio that is equal to 0.3, that is small when compared to the human one. As reported in [26], the step length of a human being is approximately 94% of the leg's height for a natural cadence. It increases for a fast cadence to approximately 116% of the leg's height, while it decreases for a slow cadence.

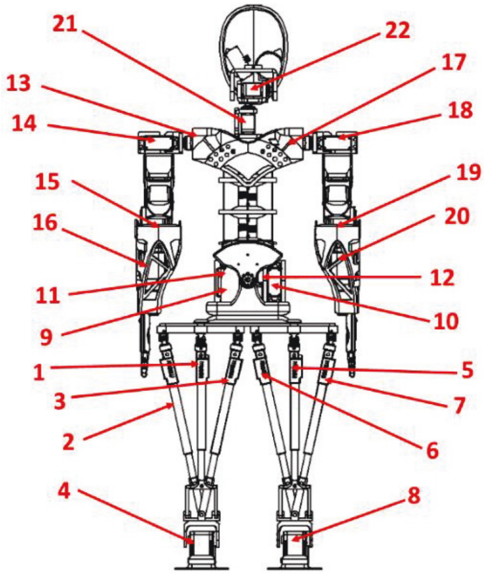
LARMbot 2 introduces parallel architectures in humanoid robots not only for the locomotion system but even in the upper body, as reported in [27-30]. The leg mechanism has been optimized for a large workspace, with a step that is approximately 0.8 times the leg height despite using a parallel architecture [31]. Furthermore, it is characterized by being singularity-free in its entire workspace [32]. The cable-driven parallel mechanism in the torso is detailed in [33-34]. Balancing LARMbot 2 is a challenging task, since its different modules – namely legs, arms, torso and head – must cooperate in a coordinated motion in order to achieve balance. For this reason, this paper presents a modular approach for the formulation of a dynamic model. First, the mechanical design of the robot is described with its six mechanical modules. Then, a brief analysis of its degrees of freedom and mobility range is reported. The center-of-gravity Jacobian, as introduced in [21-22], is evaluated for each module by using its kinematics [31-34]. The results can be used to formulate the equation of motion of LARMbot 2, in order to achieve walking balance.

3 LARMbot 2 Description

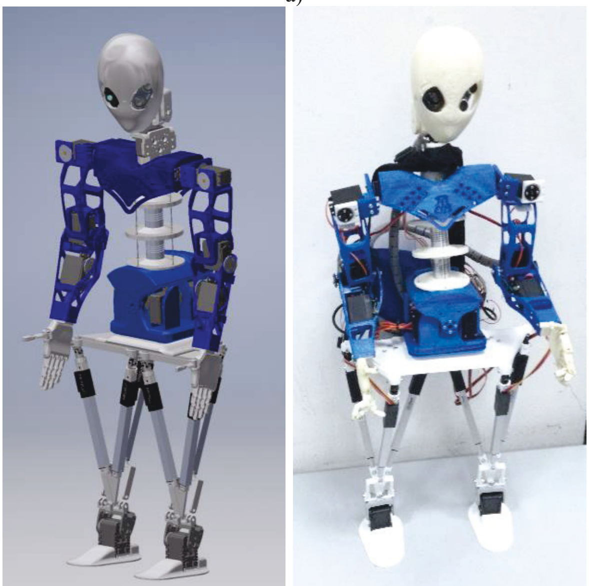
LARMbot has been developed at LARM laboratory of University of Cassino and Southern Latium in the last decade [27-28]. The first version was prototyped between 2013 and 2016, while the second version (LARMbot 2, in Fig. 1), with a different leg mechanism, has been studied since 2016. LARMbot is conceived to be a low-cost humanoid robot for service tasks. For this reason, the entire system is designed to be manufactured with commercial servomotors, Arduino and Adafruit control boards and sensors, and PLA-ABS 3D-printed components [35].

LARMbot 2 is characterized by legs and torso with parallel architectures, while arms and neck are serial mechanisms. Each leg module is characterized by a hybrid structure with a 3UPR lower-mobility parallel mechanism, first presented in [36]. The leg mechanism connects the hip to the ankle through three linear actuators that converge to a single point of the moving platform thanks to a special transmission joint mechanism. This joint ensures that the reachable workspace of the leg does not contain any singularity, as demonstrated in [31]. Furthermore, the workspace of each leg allows for a step size that is more than 0.8 times the leg height [32]. An additional rotational motor is placed on the ankle for an additional degree of freedom of the foot platform. The arm modules are 3R serial chains with two rotational degrees of freedom in the shoulder and an additional revolute joint in the elbow. The hand of LARMbot 2 is a five-finger cable-driven mechanism with a 3R finger chain that is controlled by a cable and three torsional springs. The torso module is based on the CAUTO design presented in [33], which is a cable-driven parallel manipulator. It is based on a central underactuated serial chain, composed of rigid bodies and elastic joints (E) with combined spherical and translational mobility alternating in a 3E chain. Four cables with varying length (assimilable to a SPS chain) are connected in parallel to control the relative position of the upper torso platform with respect to the hip platform. The torso module can be defined a 4SPS-(3E) parallel mechanism with 4 degrees of freedom, which are actuated by the four motors that regulate the length of each cable. The head module has 2 degrees of freedom that are actuated by servo-motors. The module is equipped with an IMU sensor, with a Wi-Fi mini-camera and with an ultrasonic distance sensor.

LARMbot 2 is 850 mm tall and has a total mass of approximately 3.60 kg, making the entire system compact and lightweight. Its payload capability for manipulation is 1.00 kg, limited by the serial structure of the arm, while the parallel architectures of torso and legs allow for a payload up to 5.00 kg. The technical specifications of LARMbot 2 are summarized in Table 1, with the size, weight and motors of each module of the prototype shown in Fig. 1, while Table 2 describes the location and the role of each actuator of the system.



a)



b) c)

Fig. 1. LARMbot 2: a) A CAD design with DoFs as in Table 2; b) 3D view; c) Prototype.

Table 1. Modules of LARMbot 2.

Module	Abbr.	W [mm]	D [mm]	H [mm]	Mass [kg]	Actuators
Left Leg	LL	160	150	400	0.5	3 leg, 1 ankle
Right Leg	RL	160	150	400	0.5	3 leg, 1 ankle
Torso	TO	200	150	300	1.2	4 cables
Left Arm	LA	60	60	360	0.5	3 arm, 1 hand
Right Arm	RA	60	60	360	0.5	3 arm, 1 hand
Head	HD	95	150	150	0.4	2 neck
LARMbot	-	320	150	850	3.6	22

Table 2. Degrees of Freedom of LARMbot 2 as in Fig. 1a.

DoF	Location	Description	DoF	Location	Description
q_1	LL	Linear actuator B	q_{12}	TO	Cable servomotor FR
q_2	LL	Linear actuator L	q_{13}	LA	Shoulder motor 1
q_3	LL	Linear actuator R	q_{14}	LA	Shoulder motor 2
q_4	LL	Ankle servomotor	q_{15}	LA	Elbow motor
q_5	RL	Linear actuator B	q_{16}	LA	Hand motor
q_6	RL	Linear actuator L	q_{17}	RA	Shoulder motor 1
q_7	RL	Linear actuator R	q_{18}	RA	Shoulder motor 2
q_8	RL	Ankle servomotor	q_{19}	RA	Elbow motor
q_9	TO	Cable servomotor BL	q_{20}	RA	Hand motor
q_{10}	TO	Cable servomotor BR	q_{21}	HE	Neck motor 1
q_{11}	TO	Cable servomotor FL	q_{22}	HE	Neck motor 2

4 Dynamics

A general equation of motion of a robot expresses the position of its center of gravity (COG) as function of external forces and moments acting on the system. While the position of the COG and the inertia of each module can be computed by using kinematics and design of each module, which are defined in [31-32] for the lower body and [33-34] for the upper body, the COG of the entire system needs to be evaluated to coordinate the motion of the module in order to achieve balance. As suggested by Sugihara and Nakamura in [21], it is possible to define a COG Jacobian which relates the position of the COG of the system with the position, velocity and acceleration of the active joints as defined by actuation vector $\boldsymbol{q}$ (see Table 2 for a definition of its components). Then, the COG Jacobian can be used both to formulate the equation of motion of the system [22] and as a basis for a balancing method for the absorption of external disturbances [21].

By approaching the problem with a modular approach, it is possible to write the position of the center of gravity $\boldsymbol{g}_i$ of the i^{th} module as

$$\boldsymbol{g}_i = \boldsymbol{f}_i(\boldsymbol{q}_i) \tag{1}$$

where the n DoF variables of the i^{th} module are expressed as in Table 2 by

$$\boldsymbol{q}_i = (q_{i,1} \quad \cdots \quad q_{i,n}) \tag{2}$$

and $\boldsymbol{f}_i$ is a vector of m functions that solve the forward kinematic problem of the module. The analytical expression for $\boldsymbol{f}_i$ is straightforward for the serial architectures of LARM-bot (head, arms) and can be found in previous works for leg and torso mechanism [31-34, 36].

Therefore, the velocity of the i^{th} center of gravity can be expressed as

$$\dot{\boldsymbol{g}}_i = \frac{\partial \boldsymbol{f}_i}{\partial \boldsymbol{q}_i}\dot{\boldsymbol{q}}_i \tag{3}$$

From Eq. (3), the COG Jacobian can be defined as

$$\boldsymbol{G}_i = \frac{\partial \boldsymbol{f}_i}{\partial \boldsymbol{q}_i} = \begin{bmatrix} \frac{\partial f_{i,1}}{\partial q_{i,1}} & \cdots & \frac{\partial f_{i,1}}{\partial q_{i,n}} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_{i,m}}{\partial q_{i,1}} & \cdots & \frac{\partial f_{i,m}}{\partial q_{i,n}} \end{bmatrix} \tag{4}$$

By differentiating again with regards to time, it is possible to obtain the acceleration of the center of gravity of each module as

$$\ddot{\boldsymbol{g}}_i = \dot{\boldsymbol{G}}_i\dot{\boldsymbol{q}}_i + \boldsymbol{G}_i\ddot{\boldsymbol{q}}_i \tag{5}$$

Equation (5) can be combined with the equations of all the other modules to obtain a general equation for the entire robot as

$$\ddot{\boldsymbol{g}} = \dot{\boldsymbol{G}}\dot{\boldsymbol{q}} + \boldsymbol{G}\ddot{\boldsymbol{q}} \tag{6}$$

The external forces acting on the i^{th} module can be expressed as

$$\boldsymbol{F}_i = \boldsymbol{M}_i\ddot{\boldsymbol{g}}_i + \boldsymbol{b}_i(\boldsymbol{g}_i, \dot{\boldsymbol{g}}_i) \tag{7}$$

where $\boldsymbol{M}_i$ is the mass matrix of the i^{th} module. It is possible to combine that equation for each of the six modules as

$$\begin{bmatrix} \boldsymbol{F}_1 \\ \vdots \\ \boldsymbol{F}_6 \end{bmatrix} = \begin{bmatrix} \boldsymbol{M}_1 & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \ddots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{M}_6 \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{g}}_1 \\ \vdots \\ \ddot{\boldsymbol{g}}_6 \end{bmatrix} + \begin{bmatrix} \boldsymbol{b}_1 \\ \vdots \\ \boldsymbol{b}_6 \end{bmatrix} \tag{8}$$

to express

$$\boldsymbol{F} = \boldsymbol{M}\ddot{\boldsymbol{g}} + \boldsymbol{b} \tag{9}$$

It is possible to write the actuation forces $\boldsymbol{\tau}$ in the active joint space as a function of the external forces by using the COG Jacobian of the whole robot, as

$$\boldsymbol{\tau} = \boldsymbol{G}^{\boldsymbol{T}}\boldsymbol{F} \tag{10}$$

Thus, the equation of motion of the robot can be formulated by substituting the expression for $\boldsymbol{F}$ of Eq. (9) in Eq. (10), and then Eq. (6) in the resulting equation, to get

$$\boldsymbol{\tau} = \boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{B}(\boldsymbol{q},\dot{\boldsymbol{q}}) \tag{11}$$

where $\boldsymbol{H}$ is the inertia matrix, defined as

$$\boldsymbol{H}(\boldsymbol{q}) = \boldsymbol{G}^T\boldsymbol{M}\boldsymbol{G} \tag{12}$$

and $\boldsymbol{B}$ is the term that contains centrifugal, Coriolis and gravitational forces, given by

$$\boldsymbol{B}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{G}^T\left(\boldsymbol{M}\dot{\boldsymbol{G}}\dot{\boldsymbol{q}} + \boldsymbol{b}\right) \tag{13}$$

Two different control approaches can be defined from the previous equations, as shown in Fig. 2: a first one can be based on a central control board computing the entire balancing action, by using Eq. (13), and a second one can be designed with a modular distributed approach, where the central control board only computes Eq. (9) and sends the required module COG motion to each module, which then evaluates a balancing action with Eq. (5).

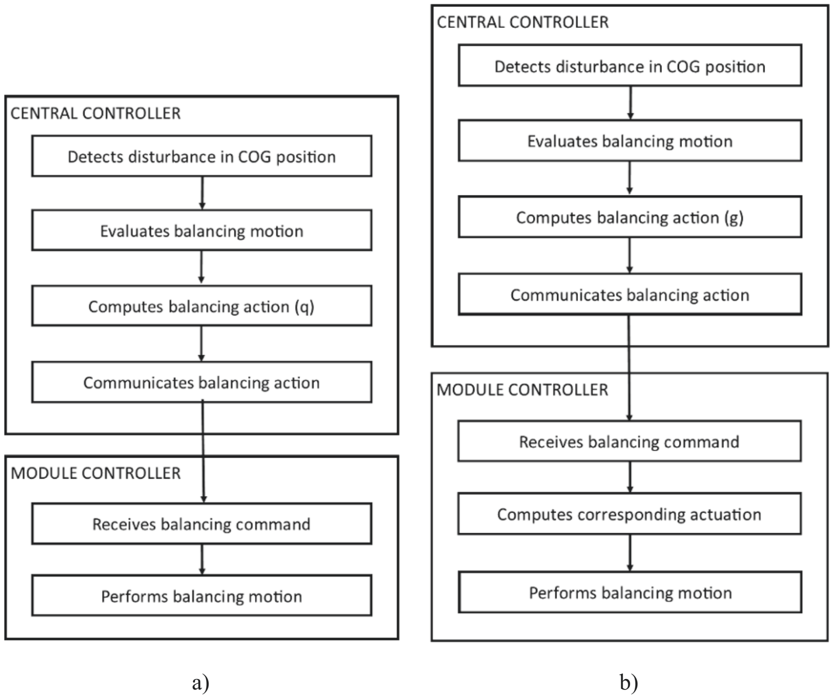


Fig. 2. A logical flowchart of the control approach: a) central control; b) distributed control.

With the first approach, the central controller computes directly the needed balancing action as actuation vector, performing the full computation by itself, as in Fig. 2a. The second approach is characterized by the central controller only computing the balancing action in term of module COG motion and the module controllers computing their resulting balancing action, as in Fig. 2b. The efficiency of the two methods depends on the hardware: the first one works better with a powerful central controller, since the module controllers only have to be able to perform actions, while the second one has the advantage of sharing the computational load for the robot kinematics (which can be complex in case of parallel architectures, and lead to multiple solutions in case of forward kinematics). However, it requires the module controllers to be able to sustain higher computational loads.

5 Conclusions

This paper presents a modular approach for the formulation of a dynamic model for LARMbot 2, a humanoid robot with parallel architectures. The state of art in humanoid robots has been analyzed, highlighting the sparse usage of parallel architectures in their mechanical designs. The mechanical design of LARMbot 2 is described with details and technical specifications of its modules. An analysis of its degrees of freedom is reported, and the center-of-gravity Jacobian is evaluated for each module and for the whole robot by using the forward kinematic problem solution developed in previous works for each module. The equation of motion of each module and of the whole LARMbot 2 is then formulated from the obtained equations, and two different control strategies are conceived: a first one is based on a central control board performing the whole balancing with the general equation of motion, and a second one is arranged with a distributed modular approach, with the central control board sharing the computational load with the module controllers. In future developments, these two control strategies will be implemented on LARMbot 2, in order to compare their performances and to define an optimal one.

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