Dynamics Simulation of a Six-Legged Mobile Robot

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SUMMARY. The paper summarizes some studies on the development of a six-legged mobile robot. The paper describes the features of the numerical model of the six legged robot developed in the Applied Mechanics Laboratory of the Energetics Department, University of Florence. The robot is currently used for didactics purposes. The availability of a simple but reliable model of the dynamics of the robot moving on a generic terrain can simplify the design of the control system and could suggest the type and the location of the necessary sensors. In this work the mathematical model of the robot is presented and a solution for its control is analyzed by means of numerical simulations.

1 Introduction

Legged robots are often slower than wheeled mobile robots, but they have the important advantage that they navigate over irregular terrain, while driving robots require a more or less flat surface. Several examples of legged robots can be found in the literature [5],[7],[4]. The typical application of this type of robots are exploiting hostile environment, security, demining etc [6].

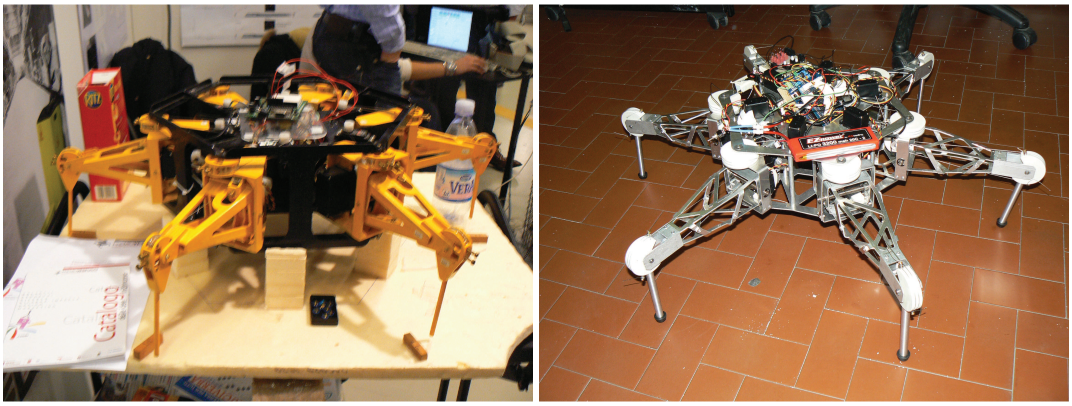
From the control point of view, the simplest case of a walking robot uses 6 legs, since this allows to implement a gait that always lifts up and repositions 3 legs, while the other 3 legs remain on the ground, providing a solid balance. Such a robot does not need to actively balance, as is required for our balancing and biped walking (android) robots.

At the University of Florence, within the courses of Robotics, the design of a legged robot has been proposed to the students in order to verify their theoretical knowledge on real design problems. The design of such type of robot involves different aspects: the mechanical structure of the robot, the choice and localization of joint actuators, the motion control of the robot etc.

At the moment this paper has been written the second prototype of the legged robot has been realized. Figure 1 a) shows the first prototype. The second robot prototype is shown in Figure 1 b).

Figures 2 show the CAD model of the second prototype. As it can be seen, the robot has a symmetrical structure (Figure 2 a)). Each leg of the hexapod is composed of three bodies connected each other by means of three revolute joints, thus has three degrees of freedom (Figure 2 b)). Each joint is actuated by a servo-motor. The kinematic structure of each leg is equivalent to an anthropomorphic manipulator. In order to reduce the inertial effects the servomotors that actuate the second and third revolute joint of each leg are located on the first body, the motion is transmitted to the joint by means of cables and pulleys.

The control of such type of robots can be divided in different hierarchical steps: the higher level control deals with the definition of robot path, in this part the robot receive a series of information about the environment from sensors, identifies the targets and the obstacles, defines its path. Starting from the desired path, the intermediate control stage plans the step, taking into account kinematic and dynamic constraints (posture control, obstacle avoidance, etc.). In the lower control stage the desired leg trajectory is translated into joint rotations.



a) b)

Figure 1: a) The first robot prototype b)the second robot prototype.

For this issue a mathematical model of the robot is necessary to test and compare different control strategies. The model includes:

- dynamics of the robot, including the interaction with a generic terrain;
- simulation of sensor measures;
- sensor fusion strategies;
- robot control and motion planning.

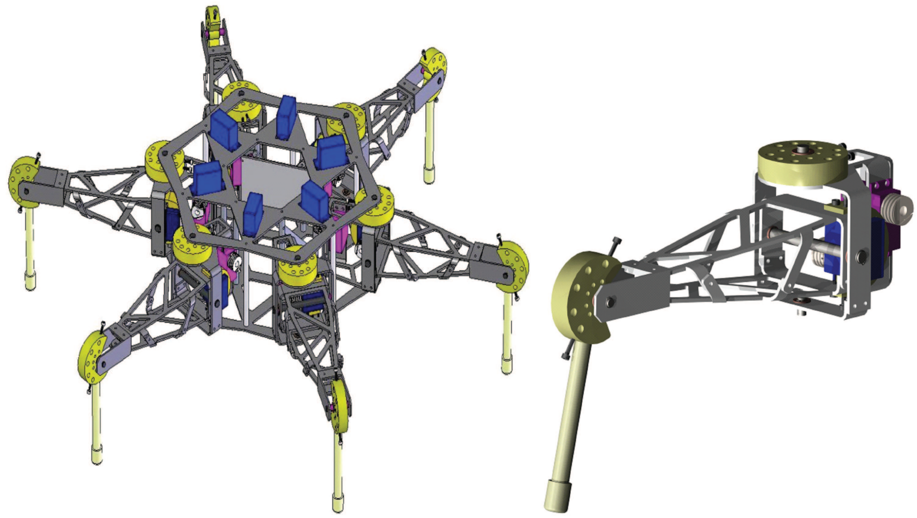
Concerning the dynamics, a multibody approach has been used to model the robot. Each link has been considered a rigid body connected with the adjacent parts by means of joints. The robot is composed of 19 bodies (the robot body and 6 legs, each leg is composed of 3 bodies) and then has 114 degrees of freedom. The bodies are connected by means of 18 revolute joints (three joints for each leg), corresponding to 90 constraint equations. A particular attention has been devoted to the model of the contact between the legs and the terrain: it is a non ideal monolateral constraint and has been modeled following the so-called Hard Finger contact model, that approximates the contact in a single point and includes the friction between the leg and the terrain.

2 Robot walking on a flat terrain

A basic assumption of the static gait (statically stable gait) is that the weight of a leg is negligible compared to that of the body, so that the total center of gravity (COG) of the robot is not affected by the leg swing. Based on this assumption, the conventional static gait is designed so as to maintain the Center of Gravity of the robot inside of the support polygon, i.e the polygon defined by the contact points between the legs and the terrain, projected on a horizontal plane. Walking gaits were first reported by D.M. Wilson in 1966. A common gait is the *alternating tripod gait*, commonly used by certain insects while moving slowly.

The *alternating tripod gait* can be summarized by the following steps (Figure 3):

- Step 1: legs 1,3,and 5 down, legs 2,4 and 6 up;
- Step 2: move backward legs 1,3,5 and forward legs 2,4,6;
- Step 3: legs 1,5 and 5 up, legs 2,4, and 6 down;
- Step 4: move backward legs 2,4,6 and forward legs 1,3,5;
- Goto step 1.



a) b)

Figure 2: CAD model of the second prototype a) The hexapod b)leg.

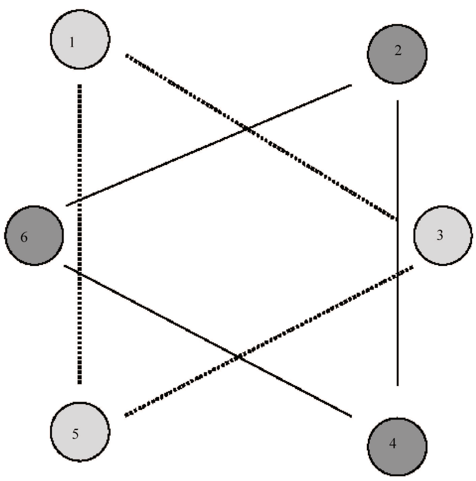


Figure 3: Tripod Gait for an Hexapod.

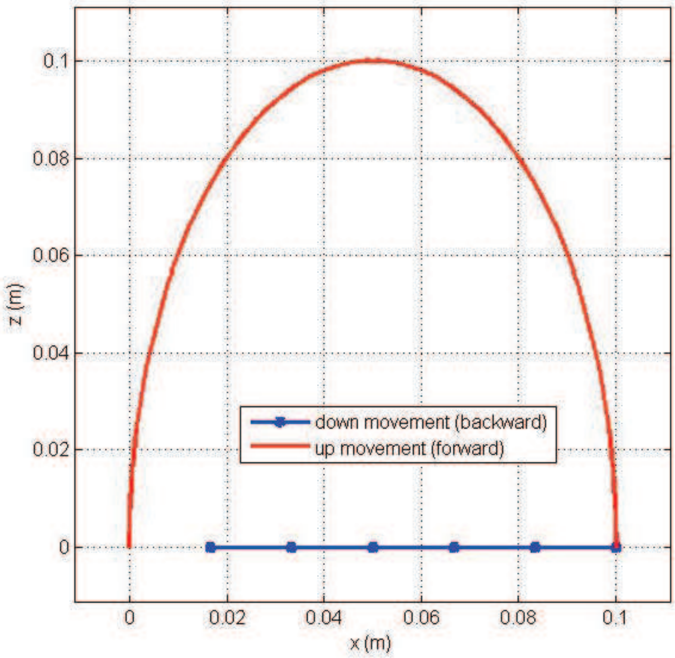


Figure 4: Leg end effector trajectory.

The movement performed by the leg when is up is a curve that starts from zero, reaches a maximum height in the vertical direction and ends in zero. In the horizontal direction the traveled distance is equal to one step length. Figure the red curve shows as an example an elliptic leg trajectory (defined with respect to the robot body). When the leg is down its end effector describes an horizontal line whose length is equal to the step length (blue curve in Figure).

Once the leg trajectory has been defined, the corresponding rotations of the robot motors have to be calculated.

3 Robot Model

3.1 Reference systems

Figure 6 represents the layout of the robot multibody model. The robot body reference system origin $O_b x_b y_b z_b$ is located in the body center of mass, the z_b axis is vertical in the starting (reference configuration), the axis x_b and y_b are defined as shown in Figure 6 On the robot main body six further reference systems $O_{0i}, x_{0i}, y_{0i}, z_{0i}$, $i = 1, ..., 6$ were defined in order to simplify the kinematic representation of the legs. The origin of these reference systems is located in the intersection between the axis of the first and second joint of each leg, according to Denavit Hartenberg notation. The z_{0_i} is directed as the axis of the first joint of each leg, the x_{oi} axis direction is defined by the vector projection on the $x_b y_b$ plane of the vector $(O_{0i} - O_b)$, the y_{0i} axis is consequently defined. Then the reference systems relative to each link of the legs can be defined according to Denavit Hartenberg notation. The $O_{1i}, x_{1i}, y_{1i}, z_{1i}$ reference systems $(i = 1, ..., 6)$, relative to the first link of each leg, has the origin coincident with O_{0i}, the z_{1i} axis is parallel to the axis of the second revolute joint, the x_{1i} axis is orthogonal to plane defined by the axis z_{0i} and z_{1i}. The $O_{2i}, x_{2i}, y_{2i}, z_{2i}$ reference systems $(i = 1, ..., 6)$, relative to the second link of each leg, has the origin coincident with the intersection between the plane x_{1i}, y_{1i} and the axis of the third revolute joint of each leg, the z_{2i} axis is parallel to the revolute joint axis, the x_{2i} axis is directed as the vector $(O_{2i} - O_{1i})$. The $O_{3i}, x_{3i}, y_{3i}, z_{3i}$ has the origin located in the contact point between the leg and the terrain, the z_{3i} axis is parallel to z_{2i}, the x_{3i} axis is parallel to the vector $(O_{2i} - O_{1i})$.

The joint variables, for each leg, are the rotations $\theta_{1i}, \theta_{2i}, \theta_{3i}$ of the revolute joints. The configuration vector

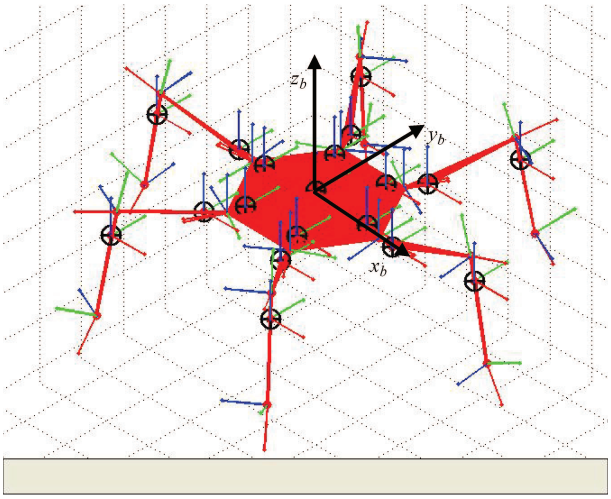


Figure 5: layout of the robot multibody model.

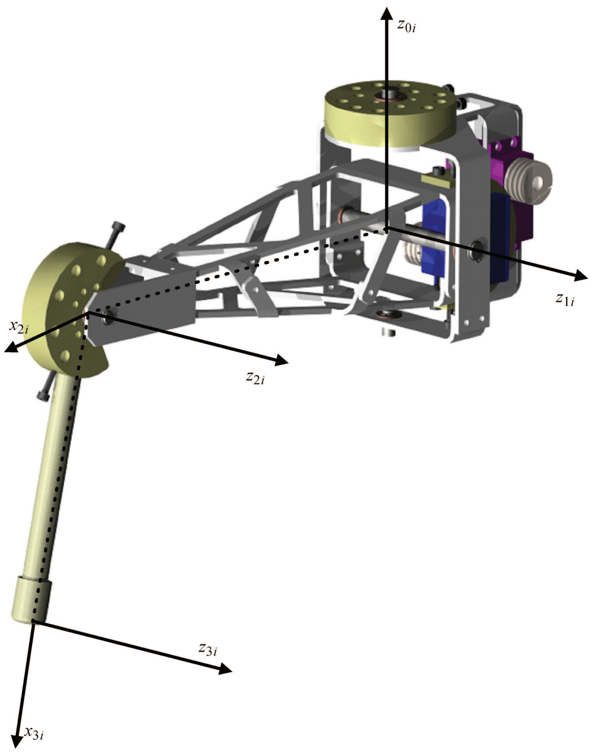


Figure 6: Leg reference systems.

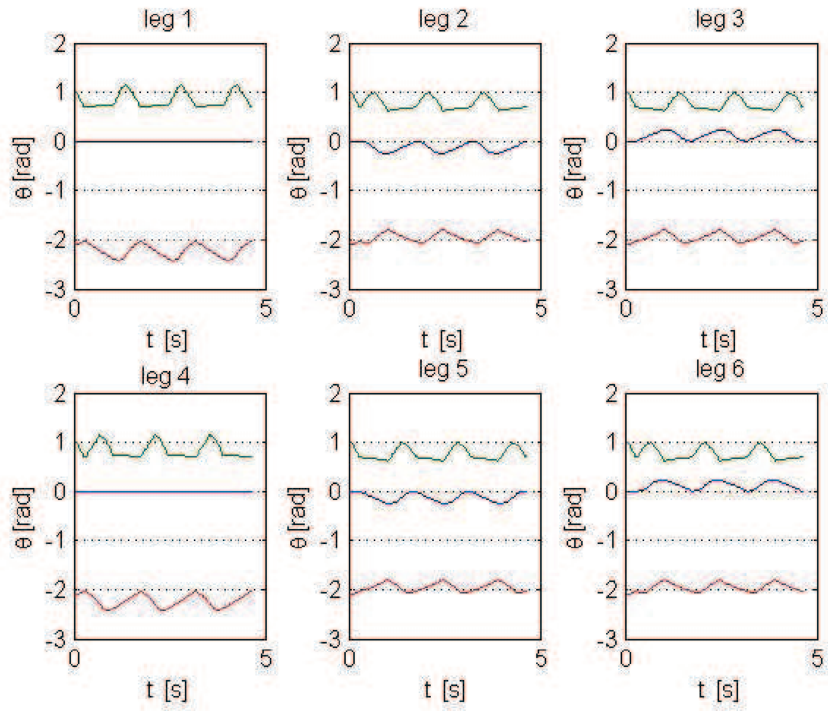


Figure 7: Leg reference systems.

$\mathbf{q} \in \mathrm{R}^{18}$, is thus defined as:

$$\mathbf{q} = \begin{bmatrix} \theta_{1,1} \\ \theta_{2,1} \\ \theta_{3,1} \\ \dots \\ \theta_{3,6} \end{bmatrix} . \tag{1}$$

Figure 7 shows the rotations corresponding to the end effector trajectory described in the preceding section and represented in Figure 2.

3.2 Robot kinematics

Given the configuration vector $\mathbf{q}$, the position of each contact point $P_i \equiv O_{3i}$ with respect to the main body reference system and the relative orientation between the reference system $O_{3i}, x_{3i}, y_{3i}, z_{3i}$ and $O_b x_b y_b z_b$ can be calculated multiplying the homogeneous transform matrices (*direct kinematics*):

$$\begin{aligned} \mathbf{T}_{3i}^{b} &= \mathbf{T}_{0i}^{b}\mathbf{T}_{1i}^{0i}\mathbf{T}_{2i}^{1i}\mathbf{T}_{3i}^{2i} = \\ &= \begin{bmatrix} c_{01,i} & -s_{01,i} & 0 & a_{01,i}c_{01,i} \\ s_{01,i} & c_{01,i} & 0 & a_{01,i}s_{01,i} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_1 c_{23} & -c_1 s_{23} & s_1 & c_1(a_{2,i}c_2 + a_{3,i}c_{23}) \\ s_1 c_{23} & -s_1 s_{23} & -c_1 & s_1(a_{2,i}c_2 + a_{3,i}c_{23}) \\ s_{23} & c_{23} & 0 & a_{2,i}s_2 + a_{3,i}s_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{2}$$

where $c_1 = \cos\theta_{1,i}$, $s_1 = \sin\theta_{1,i}$, $c_{23} = \cos(\theta_{2,i} + \theta_{3,i})$ etc. The angles $\theta_{0,i}$ represents the angles between the axis $x_{0,i}$ and x_b and are constant.

The control of the robot is defined calculating the position of the end effector of each leg with respect to the body reference system. Assigned the end effector position $\mathbf{p}_i^b = [p_{x,i}^b, p_{y,i}^b, p_{z,i}^b]^T$ the objective is then the definition of the leg joint angles $\theta_{1,i}, \theta_{3,i}, \theta_{3,i}$ (*inverse kinematics*). The solution of this problem is straightforward and is

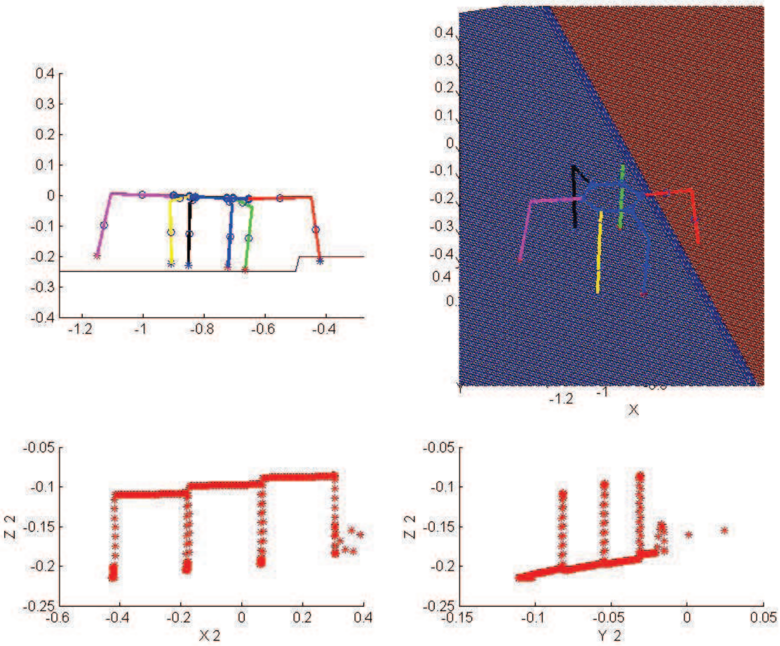


Figure 8: Simulation of the robot traveling through a terrain that presents a downhill step.

presented in several robotics textbooks. Indicating with $\mathbf{p}_i^0 = [p_{x,i}^0, p_{y,i}^0, p_{z,i}^0]^T$ the position of the end effector with respect to the leg reference system 0 ($[\mathbf{p}_i^0, 1]^T = (\mathbf{T}_{0i}^b)^{-1}[\mathbf{p}_i^b, 1]^T$), the angles $\theta_{1,i}, \theta_{2,i}, \theta_{3,i}$ can be calculated following, for example, the procedure described in [8].

3.3 Robot dynamics model

The dynamics of the robot has been analyzed by means of a multibody model realized in the Matlab/Simulink environment. All the joints (revolute)have been considered ideal, the body and the leg links were considered rigid. The inertial properties of each component of the robot was defined on the basis of the corresponding CAD solid model and of the material properties. The contact force has been modeled following the so-called Hard Finger contact model, that approximates the contact in a single point and includes the friction between the leg and the terrain: the normal component of the contact force (normal to the terrain in the contact point) is calculated as a function of the indentation between the leg and the terrain. In other terms the terrain is considered as a non-linear spring-damper element. The tangential force is proportional to the normal one and its direction is opposite to the relative leg/terrain speed in the contact point. Figure 8 shows an example of simulation of the robot dynamics when it travels through a terrain that presents a downhill step.

4 Conclusions and future developments

The University of Florence researchers, within the courses of Robotics, designed a legged robot in collaboration with the students in order to verify their theoretical knowledge on real design problems. The design of such type of robot involves different aspects: the mechanical structure of the robot, the choice and localization of joint actuators, the motion control of the robot etc.. A prototype of the robot is currently realized and the first experimental tests are being performed. Future works will include a more robust control, especially on terrains presenting asperities or steps, that will include the acquisition of measures from different types of sensors (accedlerometers, INS systems, etc.). For example, in order to estimate the relative position between the robot and the terrain a system of accelerometers has been designed. The control system will takes into account the value of the contact forces and the robot configuration estimated by the accelerometers: the robot walking on generic terrains (including irregularities, gradients, steps) towards a given target, will seek to keep a constant configuration.

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