SYNTHESIS AND RAPID PROTOTYPING OF MOTION FOR A FOUR-LEGGED MAMMAL-STRUCTURED ROBOT

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ABSTRACT: This paper presents an innovative motion synthesis method for a quadruped robot, which involves a simultaneous transfer of two of the robot's legs, along with its body. Motion synthesis is carried out for straight-line and rotational motion. The solution to the inverse kinematics problem of the robot's legs is given, which makes it possible to determine their articulated angles. The motion synthesis takes the robot's center of gravity and zero moment point into consideration. The robot's motion simulation results are presented. Experimental research was carried out by rapid prototyping method i.e. using a multifunctional card and the Real Time Windows Target toolbox in an environment similar to the one used during simulation research, which makes research process fast and easy. The conducted simulation and experimental research verified the correctness of the proposed innovative motion synthesis method.

Keywords: *Motion Control, Kinematics, Animation and Simulation, Rapid Prototyping, Education Robotics*

1. INTRODUCTION

Designing walking robots is a very hard and complex task. One of the common problems is motion synthesis, which is far more difficult in case of discrete locomotion, comparing to continuous one. Another problem is the dynamics analysis of such robots.

Quadruped robots have various kinematic structures. Most commonly used is the structure of a mammal and a crab, less commonly of an insect. Four-legged robots usually move using a statically stable walk, transferring only one leg at a given moment. This coincides with different number of motion phases, e.g. 4 [6], 6 [1] and 8. In the case of a statically stable walk, 4 phases of the robot's motion are associated with transferring of the robot's single leg and the other with the movement of the body, so as to assure a proper static stability. In these types of walks, during the whole movement phase, its center of gravity's projection should stay inside the support polygon. This of course gives best results, when the robot moves on a horizontal surface. It is not uncommon nowadays to find the movement of the quadruped robot to be dynamically stable, described in such papers as [2,3,4]. In this case, the robot's motion is practically from 2 to 4 times faster than a statically stable walk. It requires, however, a certain gait stability. This can be ensured by using adequately large feet [7] or a motion stability system [2,3] which can generate the robot's legs movement accordingly or, for example, move the counterweight mass.

Overall, there are 2 main ways of generating a robot's movement: biologically inspired and executed on the basis of the motion synthesis. The biologically inspired methods often use the idea of a central pattern generator. The robot's movement is executed via coupled oscillators e.g. [4] or as a so-called cell network. The main disadvantage of the rhythm generator approach is the difficulty with adjusting the generator's parameters in order to execute the desired motion. Usually, this method is used only to execute the robot's forward motion, when in nature both animals and humans can use this method also for turning around.

Authors generating the robot's motion via synthesis often design its walk to be simple. As a consequence, there is a lack of fluency in the robot's body movement, e.g. legs transfer whereas the body remains steady, or the body moves whilst feet are steady [1] or execute a slow, statically stable walk, consisting of 4 phases [6]. Very often, the authors concentrate only on the forward motion [1,2] executing other types of motion, like rotation or turning in a very simple way [6].

A more sophisticated motion is hardly ever executed [3]. Probably the most significant achievement in quadruped robots locomotion was implementation of motion algorithms on the BigDog robot by Boston Dynamics [3]. BigDog was destined to move in rough outdoor terrain that is too steep, rutted, rocky, wet, muddy, and/or snowy for conventional vehicles. BigDog has about 50 sensors and a variety of locomotion behaviors.

A quadruped robot named Johnny, described in this paper, is a small simple machine developed within a low cost project. It is designed mostly for research study.

2. FOUR-LEGGED ROBOT

The robot's kinematic structure is shown in Fig. 1a. Each leg has three active degrees of freedom (Fig. 1b). When numbering the legs, the first digit is the segment's number, whereas the second is the leg's number. Legs are numbered form 1 to 4. Fig. 1 shows the body angles: inclination, tilt and yaw (α, β, γ respectively), *j*-th leg joint angles ($\theta_{i.j}$), where: i = 1..5, j = 1..4 and coordinate systems attached to the robot's body as well as to *j*-th leg. The robot is composed of the following main components: body – segment *0*, hips – segments *1.j*, thighs – segments *2.j*, shins – segments *3.j* and feet – segments *4.j* and *5.j*. Each of the robot's legs is powered by 3 servomechanisms, which carry out $\theta_{1.j}$ - $\theta_{3.j}$ rotations of the robot's *j*-th leg. The robot's feet can make free $\theta_{4.j}$ and $\theta_{5.j}$ rotations. Change of angles $\theta_{4.j}$ is carried via gravity and inertia forces affecting the robot's legs. A Change of angles $\theta_{5.j}$ on the other hand is a consequence of the robot's rotation around the z-axis. The robot's body length is L_0 = 0.25 m, width W_0 = 0.18 m, height H_0 = 0.1 m, thigh and shin length $l_2 = l_3$ = 0.08 m. The robot's weights are: total m = 2.522 kg, body m_0 = 1.382 kg, hip m_{1j} = 0.094 kg, thigh m_{2j} = 0.034 kg, shank m_{3j} = 0.08 kg, upper foot part m_{4j} = 0.017 kg, lower foot part m_{5j} = 0.06 kg.

Fig. 2a shows robot's design in Autodesk Inventor program and the numbering of the robot's legs. A model of the real robot is shown in Fig. 2b. In order to conduct the experimental research, a prototype servomechanism controller was designed. The robot's knees and hips are equipped with potentiometers for measuring its legs' joint angles.

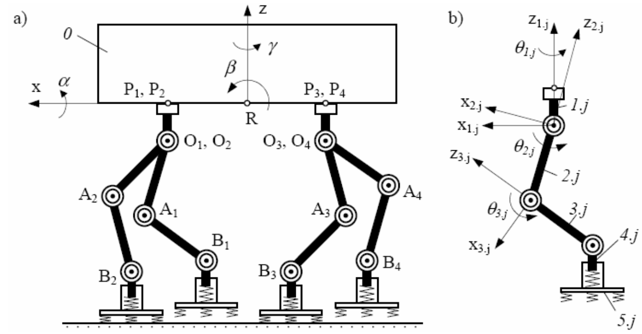

Fig. 1. Four-legged robot kinematic structure (a), joint angles designations and coordinate systems for the *j*-th leg (b)

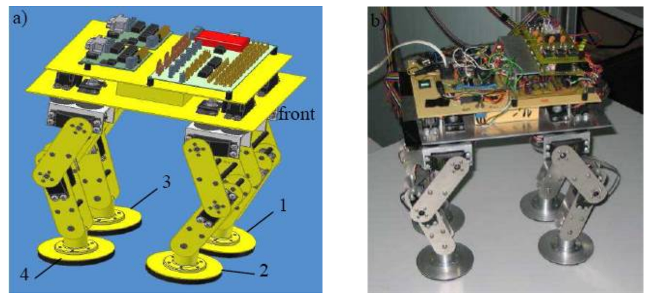

Fig. 2. Robot developing process: model of robot's mechanism (a) and the robot's construction (b)

3. MOTION SYNTHESIS

This paper describes the innovative motion synthesis method of the robot on a horizontal surface. Innovation of this method is connected with transferring of two robot's legs along with the body, resulting in only two motion phases. As a consequence, the movement is faster than typically and the body moves continuously.

The robot can execute following types of motion: straight-line (forward or backward), rotational, side, turning (in a given radius), body raising or lowering. During each of the robot's motions (except raising or lowering the body), two legs are being transferred, i.e.: 1 and 4 or 2 and 3.

This paper focuses on two types of the robot's body motion: straight-line and rotational. Paper [7] discusses the ground reaction forces distribution problem for this robot.

Forward or backward straight-line body motion depends on the desired velocity of the motion u_{RC}, step length l, leg transfer height h and the robot's body position height H. Firstly, one has to determine the R-point coordinates of the body, as well as B_j points of the robot's feet (Fig. 1) in a OXYZ absolute coordinate system. R and B_j point coordinates in OXYZ system are described using 4-degree polynomials in time t, which makes their velocity and acceleration functions continuous.

The robot's straight-line motion is divided into 3 stages:

- acceleration – body is accelerated from $u_R = 0$ to u_{RC}, whereas at the same time legs 1 and 4 transfer half of the nominal value of step (l / 2),
- steady motion – body moves with a velocity $u_R = u_{RC}$, and legs (1 and 4 or 2 and 3) transfer with a given step length l,
- braking – body is decelerated from $u_R = u_{RC}$ to 0, whereas legs (1 and 4 or 2 and 3) transfer half of the nominal value of step (l / 2).

In case of the robot's body rotation around z-axis, the same parameters are taken into consideration as with straight-line motion, but with desired angular velocity of $\dot{\gamma}_C$ instead of u_{RC}.

During one full rotation cycle, the angular velocity of the robot's body $\dot{\gamma}$ changes from 0 to $\dot{\gamma}_C$, and then from $\dot{\gamma}_C$ to 0.

As a result of both rotation cycles, the robot's body rotates by:

$$\Delta\gamma = 125\pi\, l/180 \text{ rad} \tag{1}$$

Before beginning the rotation, the robot is in its initial position, where distances between B_j points of left and right feet are $2r = d$, and front and back $c + 2l_0$. As a result, distance between B_j and R points after projecting it on the Rxy plane are (Fig. 3):

$$R_{B0} = \sqrt{r^2 + (c/2 + l_0)^2} \tag{2}$$

The initial γ_{Bj} angles are:

$$\gamma_{B0} = \text{atan}\left[r/(c/2 + l_0)^2\right] \tag{3}$$

During the body's first rotation cycle, angles γ_{Bj} change from γ_{B0} to $\gamma_{B0} + \Delta\gamma/2$, and during the second cycle from $\gamma_{B0} + \Delta\gamma/2$ to γ_{B0}, so after two rotation cycles robot's legs return to their initial positions in relation to the body. In a situation when the robot's body rotates left, legs 1 and 4 are transferred during its first rotation cycle, whereas legs 2 and 3 transfer during its second cycle. If the body rotates right, the situation is reversed.

Knowing the feet B_j points coordinates in an absolute OXYZ system; one can transform these coordinates into an Rxyz robot-related system. Next, it is necessary to solve an inverse kinematics problem by determining the angles in the robot's joints $\theta_{i.j}$.

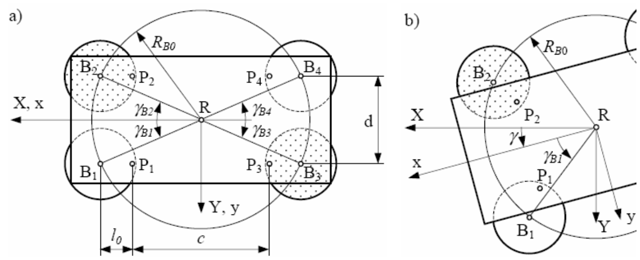

Fig. 3. Illustration of robot's rotational motion

These angles are determined from:

$$\theta_{1.j} = \text{atan}\,2\left(y_{Bj} - y_{Oj},\, x_{Bj} - x_{Oj}\right) \tag{4a}$$

$$\theta_{2.j} = \text{atan}\,2\left(-x_{1Bj}, -z_{1Bj}\right) - \text{atan}\,2\left(l_3 \sin\theta_{3.j}, l_2 + l_3\cos\theta_{3.j}\right) \tag{4b}$$

$$\theta_{3.j} = -\text{atan}\,2\left[\pm\,\text{sqrt}\left(1 - D_j^2\right), D_j\right] \tag{4c}$$

$$D_j = \left(x_{1Bj}^2 + z_{1Bj}^2 - l_2^2 - l_3^2\right)/2l_2l_3 \tag{4d}$$

where: x_{1Bj}, z_{1Bj} - B_j point coordinates in a $O_jx_{1.j}y_{1.j}z_{1.j}$ system, x_{Oj}, y_{Oj}, x_{Bj}, y_{Bj} - O_j and B_j points coordinates in a robot's Rxyz system.

For the known values of joint angles $\theta_{i.j}$ one determines their angular velocities and accelerations as well as PWM servomechanism control $u_{i.j}$ values.

Parallel to the robot's movement synthesis, its theoretical center of gravity (CG) and zero moment point (ZMP) position in a Rxyz robot-related system is taking into account as well.

The robot's center of gravity coordinates are calculated from:

$$w_{CG} = \frac{m_0 w_0 + \sum_i \sum_j m_{i.j} w_{i.j}}{m} \tag{5}$$

where: i - robot's segment number in a given leg, j - leg number, w_0, $w_{i.j}$ - center of gravity coordinate, $w = \{x, y, z\}$, m_0 - body mass, $m_{i.j}$ - segment mass i belonging to leg j, m - robot's total mass.

The robot's masses distribution in an Rxz plane is shown in Fig. 4a (dimensions in mm). On the basis of the center of gravity's coordinates, the force components acting on the robot's center of gravity is being calculated (resulting from gravity and inertia forces):

$$\mathbf{G} = -m_0(\ddot{\mathbf{r}}_0 - \mathbf{g}) - \sum_i \sum_j m_{i.j}(\ddot{\mathbf{r}}_{i.j} - \mathbf{g}) = -m(\ddot{\mathbf{r}}_{CG} - \mathbf{g}) \tag{6}$$

where: $\mathbf{r}_0$ - vector pointing to the body's center of gravity, $\mathbf{r}_{i.j}$ - vector pointing to the i.j segment mass center,

$\mathbf{r}_{CG}$ - vector pointing to the robot's center of gravity, $\mathbf{r}_{CG} = [x_{CG}, y_{CG}, z_{CG}]^T$, $\mathbf{g}$ - gravity vector, $\mathbf{g} = [0, 0, -g]^T$, $g = 9.81$ - Earth's gravity acceleration).

Zero moment point (ZMP) is calculated on the basis of gravity and inertia forces acting on the robot's center of gravity (Fig. 4b). ZMP coordinates are:

$$x_{ZMP} = x_{CG} - (H + z_{CG}) G_x / G_z \tag{7a}$$

$$y_{ZMP} = y_{CG} - (H + z_{CG}) G_y / G_z \tag{7b}$$

$$z_{ZMP} = -H \tag{7c}$$

During the robot's motion synthesis both the robot's center of gravity and zero moment point are taking into account. The robot's motion is executed in such a way, that at any given point in time, the zero moment point's position is in the support plane created by the supported feet.

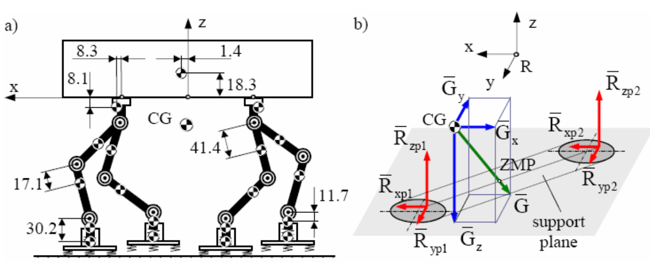

Fig. 4. Robot's masses distribution in Rxz plane (a), zero moment point (ZMP) and forces acting on the robot (b)

4. SIMULATION RESEARCH

The robot's movement was performed, during the simulation research. The whole robot's software was written in C language. An s-function of the Matlab program has been created based on that. Ultimately, the aim of the software was determination the PWM control for robot's servos.

The scheme of software in the simulation was as follows:

a) The choice of the type of movement,

b) Calculation of velocities,

c) Synthesis of R and B_j points movement (Fig. 1) (for rotating movement and turning additionally turn γ) in respect to OXYZ absolute coordinate system,

d) Transformation of coordinates of B_j points to Rxyz system,

e) Determination of $\theta_{i,j}$ angles (inverse kinematics problem),

f) Calculation of joints' angular velocities and accelerations,

g) Determination of coordinates of robot's center of gravity x_{CG}, y_{CG}, z_{CG} in robot's Rxyz system,

h) Determination of the component forces G_x, G_y, G_z acting on the robot's center of gravity in robot's Rxyz system,

i) Determination of a theoretical position of zero moment point x_{ZMP}, y_{ZMP}, z_{ZMP} in robot's Rxyz system,

j) Determination of control signals for robot's servos $u_{i,j}$.

This paper presents the results of simulation research for the robot's forward movement and left rotation.

The first presented simulation was realized for the longitudinal movement forward. The simulation was done for data: p_{RC} = 0.03 m/s (velocity of the desired movement), l = 0.06 m (step length), h = 0.03 m (step height), l_0 = 0.02 m (see Fig. 3a) and H = 0.22 m (body position height).

Simulation results are presented in Fig. 5. Coordinates of the robot's center of gravity (Fig. 5a) change mostly along the z axis, which is connected with the cycles of raising and lowering of the legs. From Fig. 5b it can be seen that only x coordinate of ZMP point changes during forward movement of the robot. On the diagram we can observe the asymmetry, which is connected with the non-zero value of x_0 center of gravity's coordinate of the robot's body.

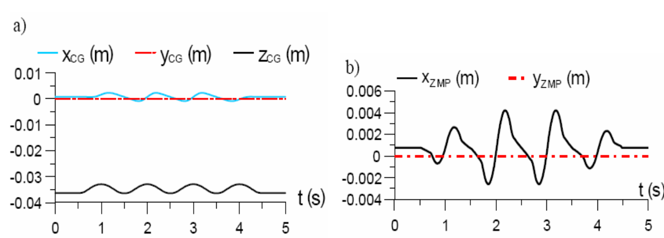

Fig. 5. The coordinates of: robot's centre of gravity (a) and ZMP (b) in a Rxyz system during forward motion

Theoretical robot's joint angles change during its forward motion obtained in the simulation is presented in Fig. 7 (thin lines) together with the analogous experimental results.

The second simulation was done for the robot's rotational movement in the left direction with the following parameters: $\dot{\gamma}_C$ = 7.5 deg/s, h = 0.03 m, l_0 = 0.02 m and H = 0.22 m.

During the robot's body rotation, its center of mass (Fig. 6) moved cyclically along the z-axis. ZMP coordinates practically did not change during the robot's body rotation (which was caused by the robot's legs symmetrical movement). Analogously as in a first simulation, theoretical robot's joint angles change during its left rotation is shown together with experimental results in Fig. 9.

The movies presenting an animation of the robot's movement are available at [5].

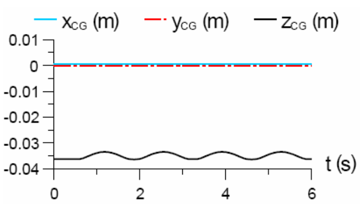

Fig. 6. The coordinates of the robot's centre of gravity in a Rxyz system during left rotational motion

5. EXPERIMENTAL VERIFICATION

In the case of experimental verification, values previously determined and saved inside the servo-controller have been used. During the robot's movement, an Advantech PCI-1710 multifunction card and a Real Time Windows Target Toolbox of the Matlab/Simulink package were used for recording the measurements.

In the first experiment, the robot was moving forward on the flooring. The robot's motion consisted of 3 stages, i.e. acceleration, steady motion and braking. The robot moved analogically to the first simulation, i.e. with a velocity of 0.03 m/s. The body position height was 0.22 m, nominal step length was 0.06 m, and the step height was 0.03 m.

Fig. 7 compares simulation and experimental research results. The figure contains change of angles at the robot's joints during straight-line motion, with their theoretical values marked with thin black lines, resulting from the conducted simulation. Designations of the joint angles agree with Fig. 1b. The last figure (Fig. 8) presents signals from the pushbutton switches in the robot's feet.

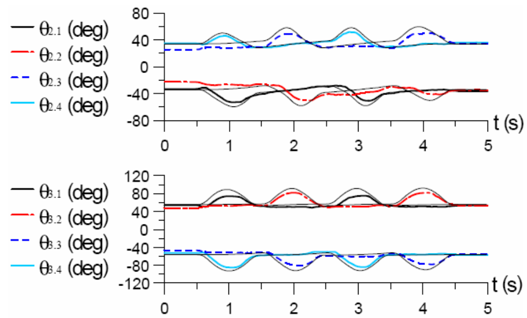

Fig. 7. Robot's joint angles change during forward motion

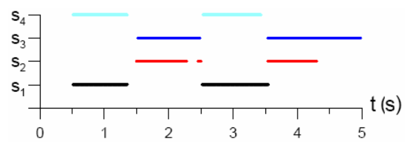

Fig. 8. Signals from pushbuttons switches - forward motion

Analyzing the robot motion (based on move presented on [5]), one can observe an asymmetry during the real robot's movement. This results in an uneven feet reaction forces distribution, which is visible during the robot's motion as well as after it stops (Fig. 8). After the robot stops, one of the pushbutton switches mounted in its feet was disconnected ($s_3 = 1$) despite the fact, that the foot was in the support stage. This happened, because the leg absorbed lesser ground reaction force than it should. This was a result of the robot's legs' joint angles errors. Moreover, during the robot's motion, while transferring legs 2 and 3, the pushbutton switch in the second foot got disconnected for a moment ($s_2 = 0$). This happened because during diagonal walk the robot kept tilting from left to right.

In the second experiment, the robot walked on a desk, turning left. Similarly to the simulation, the robot's body rotated with a maximum angular velocity of 7.5 deg/s, the body position height was 0.22 m, and the step height was 0.03 m. The results are illustrated by figures 9 and 10. Figure 9 shows the actual timings of angles at the robot's joints, with their theoretical values marked with thin black lines, resulting from the conducted simulation. The final chart (Fig. 10) presents signals from the pushbutton switches in the robot's feet.

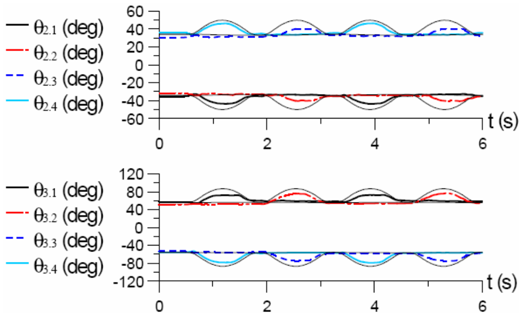

Fig. 9. Robot's joint angles change during left rotation

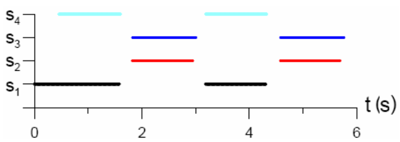

Fig. 10. Signals form pushbutton switches - left rotation

From analyzing the results and movies [5], it is obvious that the robot's rotation is more symmetrical than a straight-line motion. This time the robot's body did not tilt to such a degree. Similar to the straight-line motion, an uneven feet reaction forces distribution could be observed.

The robot described in this paper took part in many other experiments involving all kinds of motions (see [5]).

6. SUMMARY

An innovative motion synthesis method for quadruped robot taking its center of gravity and zero moment point into consideration has been presented in the paper. Robot simulation and experimental research results have been shown, including animations and movies. Experimental research was done by a rapid prototyping method. The conducted research verified the proposed motion synthesis method correctness.

From all the robot motion stability research done so far, it is clear that the zero moment point is inside the support plane for each type of the discussed robot's motions.

Results achieved in the experimental research phase show, that during the robot's movement, lots of joint angles and angular velocity errors occur. They result from different control characteristics in the support and transfer phase, which is connected with the joints backlashes and compliance.

The robot's tilts resulted from the fact, that when the phase of a given leg's motion changed from transferring to supporting or the other way around, the torques direction also changed and the drives were not able to react fast enough. Springs used in the robots feet, by introducing compliance, decreased this effect partially by softening the transition between different movement phases.

Presented in this paper robot's motion synthesis methods and methodology of robot research have features which cannot be founded in total within one from cited works.

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