Engineering Optimization of a Robot with Six Legs

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Abstract. Walking robots are becoming more widely used in human activity. Basis for achieving good quality indicators are certain basic geometric parameters. Engineering optimization was conducted in this work, of the main dimensions of the body and legs of a robot with six legs in order to ensure sustainable movement in unstructured environments and overcoming obstacles. The results, obtained from the engineering optimization, were used to make a model of the robot through 3D printing. The model was used to conduct experiments and confirm the theoretical results.

Keywords: Six-legged robot, engineering optimization, 3D Printer, Physical model

1. INTRODUCTION

Walking robots have a wide field of application. In most cases this involves movement in unstructured, dynamic environment with randomly placed obstacles, which have complex geometric parameters and various characteristics. Under specific conditions, robots must bypass or pass through obstacles. Depending on the size and location of the obstacle, as well as its technical limits, the robot must make a decision. The control panel has elements of artificial intelligence, which is supported by a targeted combination of sensors (Xochitl et al., 2013; Jayanta et al., 2014).

There are many factors, that influence the choice of the number and positioning of the legs. As it is known, the number can be 1 (rarely), 2, 3 (rarely), 4, 6, 8 or more. Their position is related to the geometry, the degrees of mobility and functional purpose of the body. We have many examples in the living nature, which serve as a model for developing robots. (Antoine et al., 2015). The authors aimed at the development of a six-legged robot. One of the essential criteria for the design is to ensure the rollover stability of the robot motion. (François, 2007). The six-component vector of external forces or moments, acting on the robot, must be balanced by the reactions in the supporting legs. Technical balance can be static or dynamic.

It is known that when walking each leg passes through four stages – lifting, moving away (it can be done by the body), stepping and moving the leg again(it can also be performed by the body). For quality kinematic movement, each leg must have three suitably oriented degrees of freedom. When the number of legs is 6 and more, quality motion (along a marked path) of the robot can be obtained in the case where some of the legs lose part of their mobility. (Trifonov et al., 2016).

In this work we conducted engineering optimization of the main dimensions of the body and legs of a robot with six legs in order to ensure sustainable movement in unstructured environments and overcoming obstacles. A model of the robot was made through 3D printing, using the results, obtained from the engineering optimization. The model is used to conduct experiments and confirm the theoretical results.

2. ROBOT DESCRIPTION AND THEORETICAL FUNDAMENTALS

2.1. Robot Construction

Below follows an overview of the walking robot, developed by the authors (Fig. 1). The batteries and the control module are mounted inside the body. Six legs with three degrees of freedom are also mounted to it.

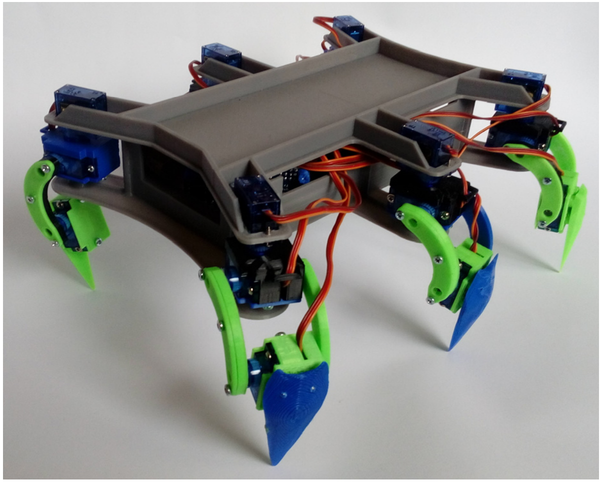

Fig. 1. General overview of the robot

All legs have similar construction, which is shown in Fig. 2. Each leg is driven by three servomotors. The axis of the first two are orthogonal ($R_1 \perp R_2$), the second and the third servomotors axis are parallel ($R_2 \| R_3$). This principle allows the tip of the leg (P point) to perform controllable spatial movements. The units are made out of PLA (Polylactic acid) using FDM (Fused Deposition Modeling) 3D printing technology.

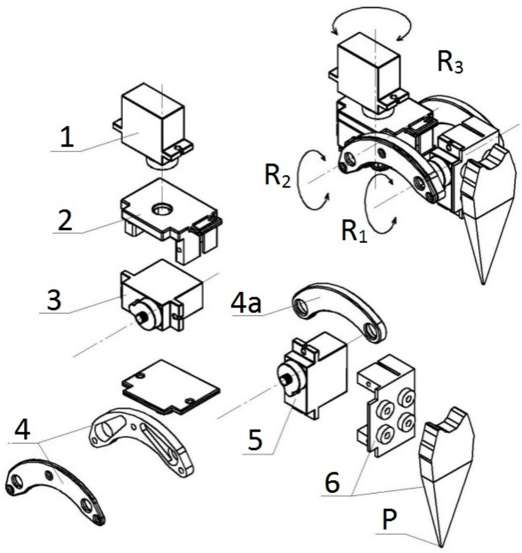

Fig. 2. Basic elements of the leg.

2.2. Control System Architecture

The control system of the robot is a controller Servotor32, which is based on ARDUINO ArcBotics [HEXY].

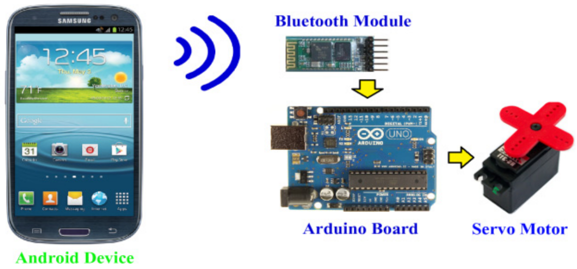

Fig. 3. Architecture of the control system

Arduino is an open source microcontroller board. It is based on easy for use open source software and hardware. Its development environment supports Mac, Windows and Linux. Large number of standard shields and sensors can be used as building blocks for rapid development of network of intelligent devices with sensing, control and Internet access. Arduino can also be connected to a SBC (Single Board Computer) Raspberry Pi 3 (Fig. 4) to extend the functionalities of the control system.

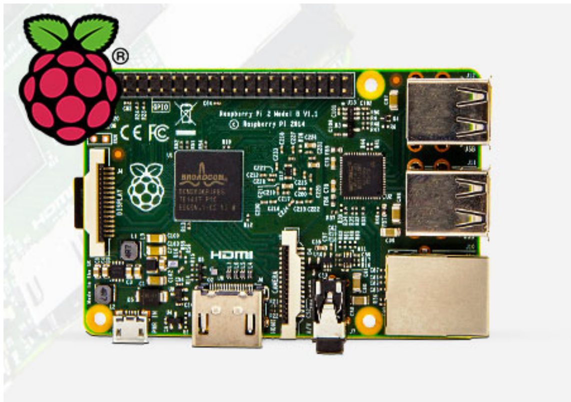

Fig. 4. Raspberry Pi 3

Raspberry Pi 3 Model B 1GB characteristics:

- Broadcom BCM2836 ARMv7 900MHz Quad Core Processor;
- 1GB RAM;
- 40pin extended GPIO (General-purpose input/output);
- 10/100 Ethernet port;
- MicroSD slot;
- Multiple Ports: 4 USB ports, Full Size HDMI, 4 pole Stereo output and Composite video port, CSI camera port & DSI display port
- Micro USB power source (element14.com/raspberripi)

2.3. Theoretical Basis

An example of a kinematic scheme of a robotic leg is shown in Fig. 5. The coordinate systems are placed following the rules of Denavit and Hartenberg (Roy et al., 2009). The parameters are displayed in Table 1. It is known that the presentation of vectors from a reference system to another is done with transformation matrix T_{ij} type:

$$T_{i,j} = \begin{bmatrix} R_{i,j} & O_{i,j} \\ 0 & 1 \end{bmatrix}, \qquad (1)$$

where $R_{i,j}$ is a 3x3 matrix, which defines the orientation of the coordinate system j related to the coordinate system i; $\rho_{ij} = [X_{ij}, Y_{ij}, Z_{ij}]^T$ is the radius vector which connects the two coordinate systems, $0=[0\ 0\ 0]^T$ is zero matrix.

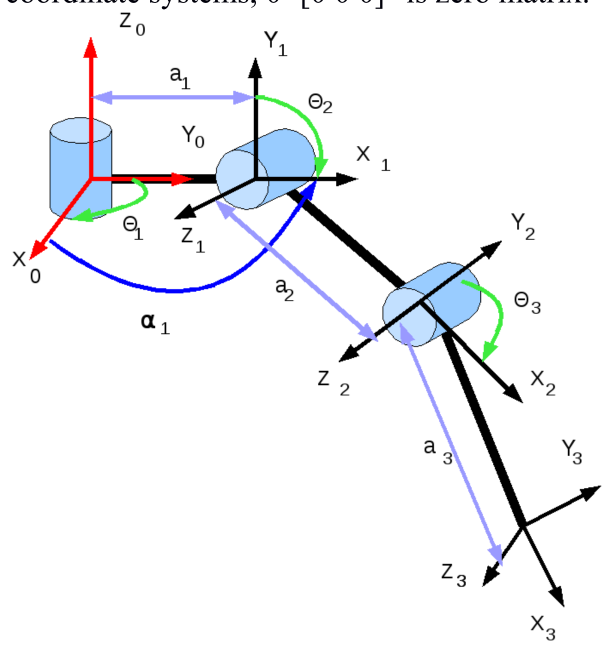

Fig. 5. Scheme of a leg with the coordinate systems of the joints

Table 1. Denavit-Hartenberg parameters for one leg (see **Fig. 5**)

Link Number	θ	α	d	a
1	θ_1	90	0	a_1
2	θ_2	0	0	a_2
3	θ_3	0	0	a_3

The location of the point P (Fig. 7) and the orientation of the foot can be determined by the following matrix:

$$T_{03} = T_{01}T_{12}T_{23}$$

$$T_{03} = \begin{bmatrix} c_1c_{2+3} & -c_1s_{3-2} & s_1 & a_1c_1 + a_2c_1c_2 + a_3c_1c_{2+3} \\ s_1c_{2+3} & -s_1s_{3-2} & -c_1 & a_1s_1 + a_2s_1c_2 + a_3s_1c_{2+3} \\ s_{2+3} & c_{2+3} & 0 & a_2s_2 + a_3s_{2+3} \\ 0 & 0 & 0 & 1 \end{bmatrix} (2).$$

where $c_1 = \cos(\theta_1)$; $c_2 = \cos(\theta_2)$; $s_1 = \sin(\theta_1)$; $c_{12} = \cos(\theta_1 + \theta_2)$ etc., a_i and θ_i are geometrical parameters (Fig. 5 and Table 1). Formula (2) is the solution of the kinematics forward problem for one leg of the robot.

It is necessary to solve the kinematics inverse problem, which is required for the design and control systems. The main purpose is to find the joint angles θ_i as function of the location of point P. This problem doesn't have a simple solution so it has to be calculated for each structure using geometrical relations. To solve the problem for the leg on Fig.5 the following equations can be applied:

$$\theta_1 = \arctan\left(\frac{x}{y}\right) \qquad (3)$$

$$\theta_2 = -\arctan\left(\frac{a_3\sin(\theta_3)}{a_2 + a_3\cos(\theta_3)}\right) + \\ + \arcsin\left(\frac{z}{\sqrt{(a_2 + a_3\cos(\theta_3))^2 + a_3^2\sin(\theta_3)^2}}\right) \qquad (4)$$

$$\theta_3 = -\arccos\left(\frac{\left(\frac{x}{\cos(\theta_1)} - a_1\right)^2 + z^2 - a_2^2 - a_3^2}{2a_2a_3}\right) \qquad (5)$$

where x, y and z are the coordinates of the point P relative to X_0, Y_0, Z_0. In general, this problem may have more than one solution. The equations (4), (5) and the joint limits, which are determined by the capabilities of the motors and design considerations of the motors, are necessary to define the workspaces and motion laws of the robot's legs.

3. DATA

The top view of the designed robot with the global dimensions and the distance between legs is show in Fig. 6. The unit`s dimensions respectively are $a_1 = 0.05$ [m], $a_2 = 0.04$ [m], $a_3 = 0.058$ [m] (Fig. 7). Joints limits in radians are relatively:

$$-\frac{\pi}{2} < \theta_1 < \frac{\pi}{2}; -1,29 < \theta_2 < 0,366,$$
$$-0,54 < \theta_3 \leftarrow 2,72$$

(see Fig. 8). The robot's elements are made out of PLA with a 3D printer. The electronic components are presented in section 2.2. Four NiMH batteries supply the servomotors and an additional battery power bank supplies the control system. Different power supplies for the control system and the motors are used, so when the motors drain different amount of current, it doesn't generate additional noise in the control system.

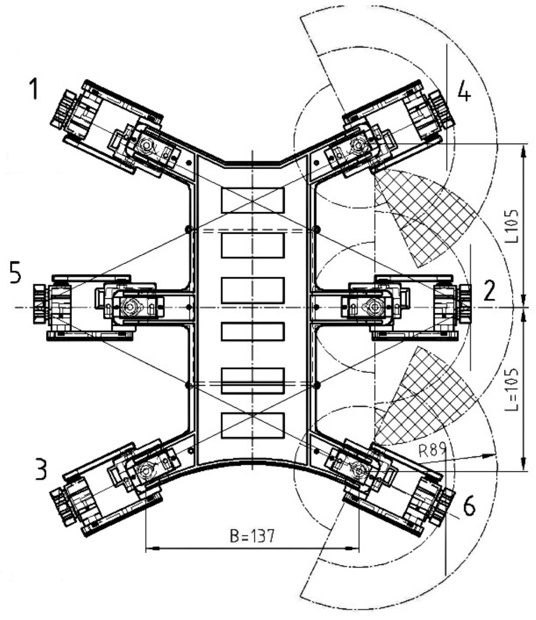

Fig. 6. Intersecting workspaces of the legs and base dimensions.

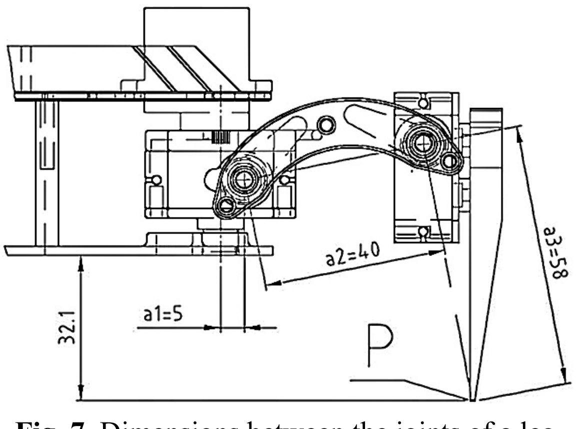

Fig. 7. Dimensions between the joints of a leg.

4. EXPERIMENTAL RESULTS

A model of six legged robot was designed and constructed (Fig. 1). The leg workspace of the robot is defined by the theoretical model formulas (4) and constructions in a CAD environment. This is the set of all possible points which point P can reach (Fig.7) only using the leg when the body of the robot is static. The results are shown in two cross-sections in planes orthogonal to each other (Fig.8). The current dimensions and joint constraints allow the max reachable height to be h_{max} = 0.0776 [m], with a maximum radius of rotation R_{max} = 0.099 [m].

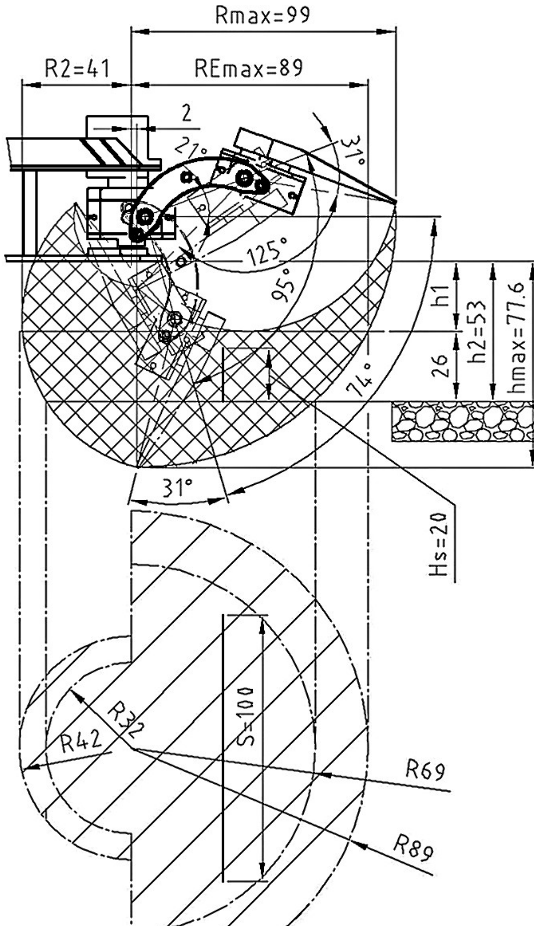

Fig. 8. Workspace of the robot's leg.

The working height for walking on a plane is considered to be h_2 = 0.053 [m], so the maximum size of a step is S = 0.1 [m] and height H_s = 0.02 [m].

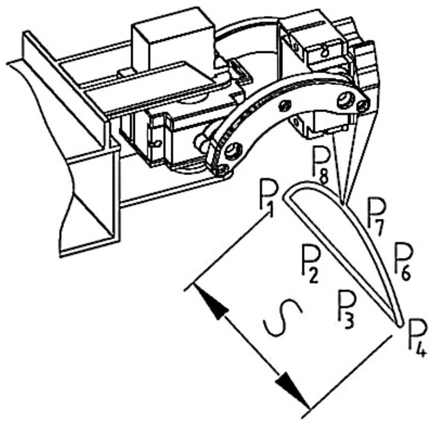

Fig. 9. A typical trajectory for motion in a straight line.

Fig. 9 displays a sample trajectory, which is used for testing the robot movements when walking in a straight line. Fig.6 shows the workspaces of 3 adjacent legs where it can be seen that the reachable areas are overlapping. Successful tests were conducted using the constructed model where legs 1, 2 and 3 move under the same law of motion – trajectory S. The legs 4, 5 and 6 move under the same law, dephased so that we always have three legs in contact with the surface.

Experiments show good functional possibilities for moving of the legs separately when the robot walks on a flat surface.

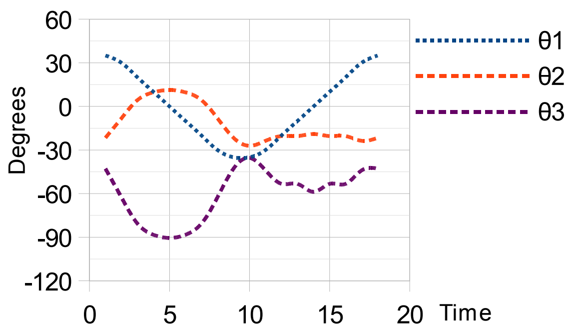

Fig. 10. Joint angles of a leg for a complete walking cycle.

Fig. 10 shows the change of the joint angles in a leg over time while walking. θ_1 is the angle of the vertical axis. θ_2 and θ_3 are the joints with parallel axes. By sending these angles to the servomotors using the control system, point P follows the trajectory on Fig. 9.

5. COMMENTS AND CONCLUSIONS

The chosen structure of the robot's legs allows motion of the foot in the space. This allows generation of different trajectories for movement of point P, which allows the use of different strategies for moving and overcoming obstacles.

The workspaces and cross-sections of the legs are defined, which is necessary for the generation of walking algorithms by the control system. The chosen walking algorithm retains static balance of the robot. A proper trajectory for moving in a straight line is chosen and we are looking for optimum proportions of the trajectory in the workspace of a leg.

The next goals of the authors are optimization of the geometric dimensions, choosing of optimal power supply and including sensors and elastic elements.

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