Diana OLEJNIK, Tomasz CHADY, Paweł Karol FRANKOWSKI

Department of Electrical and Computer Engineering, West Pomeranian University of Technology, Szczecin

doi:10.15199/48.2016.04.12

Climbing Quadruped Robot for Nondestructive Testing

***Abstract**. This paper presents design, construction and control of a quadruped robot, capable to maneuver on vertical surfaces. A nondestructive system integrated with the robot enables location and tracking of rebars in concrete structures. This paper illustrates robot manipulation in the kinematic approach and practical application of the platform dedicated for nondestructive testing.*

***Streszczenie.** W artykule przedstawiono projekt, budowę oraz sterowanie czworonożnym robotem, zdolnym manewrować na powierzchniach pionowych. Nieniszczący system zintegrowany z robotem umożliwia lokalizację i śledzenie prętów w konstrukcjach betonowych. W artykule przedstawiono manipulację robotem w podejściu kinematycznym oraz praktyczne zastosowanie platformy dedykowanej do badań nieniszczących. (**Czworonożny robot wspinający się przeznaczony do badań nieniszczących**).*

Keywords: non-destructive testing, reinforced concrete structures, quadruped robot, vacuum technology.
Słowa kluczowe: badania nieniszczące, struktury zbrojonego betonu, czworonożny robot, technologia próżniowa.

Introduction

The purpose of this paper is to present the design, construction and control of the quadruped robot, capable of maneuvering even on vertical surfaces of reinforced concrete structures. The non-destructive system integrated with the robot enables the location and tracking of the rebars in concrete structures. The robot's ability of climbing is assured by the high quality vacuum system. The prototype of the measurement platform is equipped with the ejector pumps and suction cups, which make robot adhesion dependent on the surface roughness.

This paper discusses briefly theoretical aspects of robotic manipulation. Also, computer simulations of the robot representation in a reference configuration are presented. In the last section potential of the robot platform for application in non-destructive testing is described.

Structure and Control

The project of a quadruped robot was prepared using the Autodesk Inventor Professional, 3D design software. Every moving element and actuator can be modelled in a CAD project, thereby the precise designing of the mounting parts and printing them using a 3D printer is possible (Fig. 1, 2). Printed parts are made of thermoplastic polymer Acrylonitrile Butadiene Styrene (ABS) with the print temperature in the range of 210-240ºC.

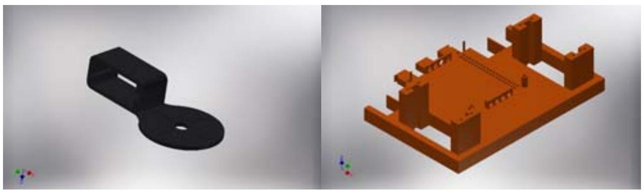

Fig.1. Autodesk Inventor - design software

Fig.2. 3D printing using UP Plus 2

To make climbing possible it is necessary to use light and strong actuators. Due to this aspect, the vacuum technique is used. The decentralized system assumes application of four ejector pumps (one per leg) equipped with the suction cups. High friction of the rubber material allows the suction cups to withstand forces, even at rapid accelerations in horizontal directions. Lifting force vertical to the surface is equal to 168 N and lifting force parallel to the surface is 225 N, at vacuum level of 60 kPa. Multistage ejector technology ensures small size of vacuum pumps with higher efficiency than the conventional technology. The pumps can operate within the feed pressure range of 0.4 to 0.6 MPa. Compressed air flow control is performed by the pneumatic electro-valves [1]. Applied solenoid valves operate on 5/2 function. The robot is driven by a Raspberry PI B+ - single-board computer. Motions of the robot legs are carried out by eight digital servos, two per leg. The required number of degrees of freedom is ensured by a 3D printed spherical bearing. Torque of the coreless motor servo is equal to 1,37 Nm, which is highly efficient. The servos are connected to a pulse-width modulation (PWM) driver. A position of electro-valves and servomechanisms are controlled by the Raspberry Pi board.

Fig.3. 3D visualization and photography of the Climbing Robot

An operating system - Raspbian, is based on the Debian/GNU Linux optimized for the Raspberry Pi hardware. This environment provides a complete graphical user interface and a console mode. Robot programming was done using Python 2 language. Additionally, for calculation and plotting Numpy and Matplotlib packages were utilized. The implemented software allows both manual and automatic robot control through a wireless communication. A major function of the software is the ability to record the measurements for a further analysis. To improve a user control system, three methods of communication with the robot were prepared. The simplest one is based on remote desktop using Virtual Network Computing software and hand control via console mode.

Another method requires the Xbox 360 controller, whose buttons are programmed to allow the robot control. In the third case, Kivy multi-touch application was implemented to enable control through a mobile or tablet. Depending on which method is selected, the robot is equipped with a Wi-Fi dongle or a Bluetooth receiver for Xbox controller.

The robot occupies the space of about 0,16 m^2 and its weight is 2.35 kg. The power supply is composed of two lithium polymer batteries. Accordingly, the only limitation of this quadruped robot is the need to provide a compressed air, to make the robot adhesive to a surface.

Robotic Manipulation

Information about relation between the motion of the joints and configuration of the robot links guarantees a precise manipulation. As it will be shown below, in order to manipulate the robot, forward kinematics are needed.

A ξ element (a Lie algebra element) describes motion of a joint

(1) $$\xi = \begin{bmatrix} \omega \\ -\omega \times q \end{bmatrix},$$

where ω is a direction of the movement and q is a point on the axis about which the joint rotates, then position of the first joint is

(2) $$g_1(\theta) = e^{\hat{\xi}_1 \theta_1} g_1(0),$$

where θ_1 is an joint angle and $g_1(0)$ is a reference configuration.

In general, the forward kinematics map of an open-chain manipulator with *n* degrees of freedom is given by

(3) $$g_n(\theta) = e^{\hat{\xi}_1 \theta_1} e^{\hat{\xi}_2 \theta_2} \cdots e^{\hat{\xi}_n \theta_n} g_n(0).$$

Product of the exponential formulas (3) describes the end-effector configuration as a function of the robot joint variables [2, 3]. This approach allows the extension of the manipulator construction to more degrees of freedom without complex mathematical calculations.

Referring to the quadruped robot, a geometric representation simplifies the analysis. Let's assume a numbering convention for the robot's leg as seen in the Fig. 4.

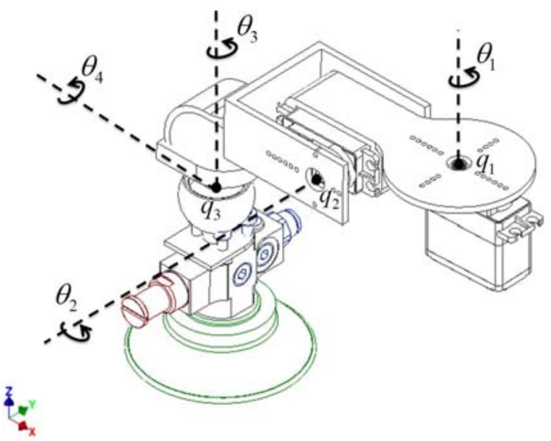

Fig.4. Scheme of robot leg with marked degrees of freedom

In this case ω for next joints will be represented by matrices:

$$\omega_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},\ \omega_2 = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix},\ \omega_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},\ \omega_4 = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}.$$

A length of the links are mapped directly from the robot's CAD project. These operation assures a high accuracy of legs position calculations. Therefore, the positions of the centers of the joints are expressed with the accuracy of 1 mm:

$$q_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},\ q_2 = \begin{bmatrix} -44 \\ -34 \\ -13 \end{bmatrix},\ q_3 = \begin{bmatrix} -124 \\ -10 \\ -72 \end{bmatrix}.$$

In order to calculate the twist's values, computer simulation was successfully applied. The results of computing, performed using the Numpy package, are as follows:

$$\xi_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix},\ \xi_2 = \begin{bmatrix} 0 \\ -1 \\ 0 \\ -13 \\ 0 \\ 44 \end{bmatrix},\ \xi_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \\ -10 \\ 124 \\ 0 \end{bmatrix},\ \xi_4 = \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \\ -72 \\ -10 \end{bmatrix}.$$

Knowledge about primary joints positions and twists' values allow to define the end configuration of the robot's leg. In correspondence to the equation (3), the placement and orientation of the fourth robot's joint is expressed by

(4) $$g_4(\theta) = e^{\hat{\xi}_1 \theta_1} e^{\hat{\xi}_2 \theta_2} e^{\hat{\xi}_3 \theta_3} e^{\hat{\xi}_4 \theta_4} g_4(0)$$

As a consequence, all suction cups of the robot can be situated accurately at the surface.

Non-Destructive Testing of the Reinforcing Steel Bars

Detecting positions of the reinforcing steel bars and evaluating the corrosion of reinforcing steel bars are important in preventing the occurrence of cracks in concrete structures. Diagnoses of reinforced concrete structures are usually carried out using technologies of a self-potential method, a radar method and an electromagnetic induction method [4].

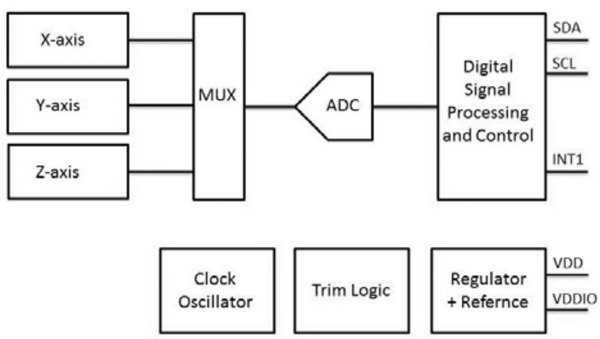

Fig.5. Sensor MAG 3110 - block diagram

In the case of a climbing quadruped robot for a nondestructive testing several aspects have to be considered in particular: dimension, weight and sensitivity of a transducer. The transducer should be easy to mount on the robot and provide quick access to measurements. For preliminary tests, a digital 3-D magnetic sensor MAG3110 was used. This magnetometer enables measurement of a magnetic field in three directions. The sensor sensitivity is 0.10 µT and an output data rate (ODR) is up to 80 Hz. For a communication with Raspberry PI the I2C serial interface is used.

The prepared software enables observation of measurements in real time through the console readout or the android application. It is possible to locate manually the rebars in concrete structures or to use the automatic algorithm.

The prototype algorithm was tested only for the simplified cases with the single reinforcing bars. Testing was carried out by moving the robot at 200 mm distance. The sensor was located h = 10 mm over the reinforcing bar.

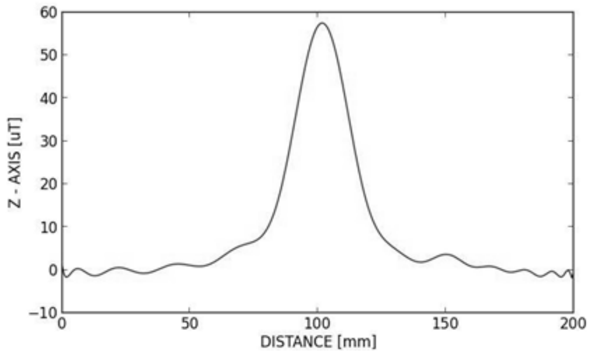

Fig.6. Result of rebars detection - one measurement with sensor placed at the height of 10 mm

The chart (Fig.6) shows a peak with a value equal to 60 µT at position of 100 mm where exactly the rebar was placed. Small variations of the signal are a result of the noises coming from the surrounding area. Device calibration has a high impact on the magnetometer readings.

Further tests were performed while increasing the distance h from the sensor to the rebar by 5 mm to the last measurement carried out for h = 100 mm.

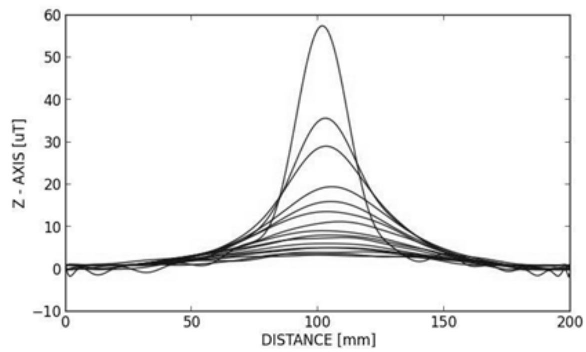

Fig.7. Result of rebars detection - measurements with sensor placed at the height of 10 to 100 mm

Next chart (Fig.7) shows multiple curves achieved for different value of h. Detectability of the rebars is decreasing with the growing distance h. In case of h =100 mm, the value of measured magnetic field is close to the level of noises. Therefore, effective tracking of the rebars at this distance from the sensor is not possible using the proposed simple transducer. On both charts can be seen a small displacement from the point designated by the rod. The reason for this is the lack of repeatability in the starting point of measurements. The problem can be solved both by appropriate software or hardware adjustments.

Conclusions

The presented study shows the practical importance of robotics in the non-destructive testing. Design of the quadruped robot and the possibility to maneuver on vertical surfaces of reinforced concrete structures was discussed. Climbing the wall using a highly efficient vacuum system was ensured. Lightweight components designed and manufactured through 3D printing technology minimized the weight of the robot. In the future the optimization of the size of the robot should mainly focus on the air management system. Four solenoid valves proved to be very heavy, which determined the total weight of the robot. Another issue arising from the use of the vacuum technology is the necessity of providing compressed air to the vacuum pumps. Therefore, the lack of full mobility of the robot is apparent, despite using the polymer batteries.

Concentrating on the modeling the gait of the robot, it should be noted that it would be worthwhile to apply reverse kinematics. Also, a method for calculating the acceleration of a robot in response to given actuator forces should be implemented. However, for the tests on a prototype robot the presented method of implementing the forward kinematics is sufficient.

By referring to results of non-destructive testing, the use of three-axial magnetometer in the initial studies turned out to be legitimate. Presented results give a clear location of steel rods at the inspected structure. In the next stage it is planned to use more accurate sensors for a more precise analysis of the magnetic field and structures assessment.

Acknowledgments

This work is supported in part by Foundation for Polish Science and cosponsored by UE under grant VENTURES/ 2013-11/5.

***Authors**: Diana Olejnik, diana_olejnik@wp.pl, Tomasz Chady, Tomasz.Chady@zut.edu.pl, Paweł Frankowski, pfrank@zut.edu.pl, West Pomeranian University of Technology, Department of Electrical and Computer Engineering, ul. Sikorskiego 37, 70-313 Szczecin, Poland*

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