Design of Multi-segment Humanoid Robot Foot

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Abstract. Most of today's humanoid robots are equipped with flat one segment feet. Only few of them have two-segment feet. Two-segment feet can be realized either with passive or active toe joint. Purpose of development of more complex robotic foot is to enable humanoid robots to walk in more natural way. In this paper will be described basic design of multi-segment humanoid foot, currently under development at the Faculty of Technical Sciences, University of Novi Sad. Paper gives short overview of human foot anatomy, and then, robotic foot design characteristics including actuation and sensing.

Keywords: Humanoid robots, multi-segment robotic foot, actuation, sensing.

1 Introduction

Active research in filed of humanoid robotics and progress of technology in last few decades led to development of number high performances humanoid robots. Current development indicates that the spectrum of robotic activities will expand significantly in the near future, particularly in the area of humanoid robotics. For a long time, robots have not been present only in industrial plants, at the time their traditional workspace, but have been increasingly more engaged in the close living and working environment of humans. This fact inevitably leads to the need of "working coexistence" of man and robot and sharing their common working environment. In near future it can be expected that humanoid robots will replace humans on some tasks which does not request human permanent presence (simple tasks at home, factory or even hospital) or moreover where human presence is not desirable (dangerous environments). For fulfillment of diverse tasks in the environment highly adapted to humans the most promising is "human-like" design. The first step that would enable robots to realize tasks in the manner and with the efficiency similar to those of humans is to make robot's structure close to that of humans. Mechanical design of humanoid robots with increased number of mechanical degrees of freedom improved significantly in past few decades, except of humanoid robot foot which remain almost unchanged in past few decades. Having on mind that human foot is one of the most complicated human body parts concerning number of bones, muscles and nerves lead us to conclusion that robot foot need to be improved in order to improve walk of humanoids.

Most of very sophisticated and excellent robots have one-segment flat foot which area is usually bigger than corresponding human foot would be, for example, Honda

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ASIMO and P2 robots [1], JOHNNIE [2], HRP-2 [3]). This cause that walk is, to great extent, unnatural.

To improve this, we believe, design of foot have to be much more complex and better suited to the needs of walk. First step in this direction is to make two-segment foot. Several research projects dealt with this issue [4-7]. Two-segment robot foot utilize, for example, BARt-UH II (Bipedal autonomous robot) developed at University of Hanover [4], ROBIAN developed at Laboratoire de Robotique de Paris [5], HRP-2LT developed at Intelligent Systems Research Institute AIST [6] and H6 developed at University of Tokyo [7].

BARt-UH, ROBIAN and HRP-2LR feet are equipped with passive (none actuated) toe joints which enable robot to perform a rolling-like motion of the foot. Additionally, ROBIAN foot adds elasticity to the passive joint between toe and the heel using torsion springs. Motion range of the ROBAIN toe joint is 60 degrees. HRP-2LR also has springs at toe joints. The expected role of the toe springs is to accumulate and release energy during robot running.

H6 foot is two segment foot with actuated toe segment. Motion range of the toe joint is 60 degrees for bending toward tibia and 15 degrees from tibia. Toe joint is actuated with DC motor. Researchers which developed H6 robot reported that walking speed is augmented by 80% by utilizing toe joint. Also, the robot was able to climb on higher stairs if toe joint was used.

2 Human Foot Anatomy

Human foot (Fig. 1) is composed of 26 bones, 33 connections (joints) and more than 100 muscles and ligaments, what is not possible to fully replicate in robotic design. Additionally, very important foot feature is sensing of ground reaction force position and its approximate intensity. Thus, this complex body organ provides the only contact of the humanoid with the ground, ensures appropriate feedback information which enables humanoid motion and permanent realization of dynamic balance.

In Table 1 are given average operational ranges of human ankle, toe and foot fingers [8], but it have to be emphasized that in most of the joints only some slight motions are possible, like rolling and sliding. True significance of these motions has not been investigated to full extent yet.

Table 1. Working angles of standard human

Ankle	pitch	-45 deg to 20 deg
	roll	-20 deg to 30 deg
Toe	pitch	-40 deg to 80 deg
Foot fingers	pitch	-40 deg to 60-80 deg

Ankle joint of humanoid robots is usually designed as 2 DOF joint with perpendicular rotation axes. In humans these axes are not perpendicular. Ankle roll axis is rotated 20 degrees toward inner foot side (counter clockwise in transverse plane) and 40 degrees clockwise in sagittal plane as it is depicted on Fig. 1.

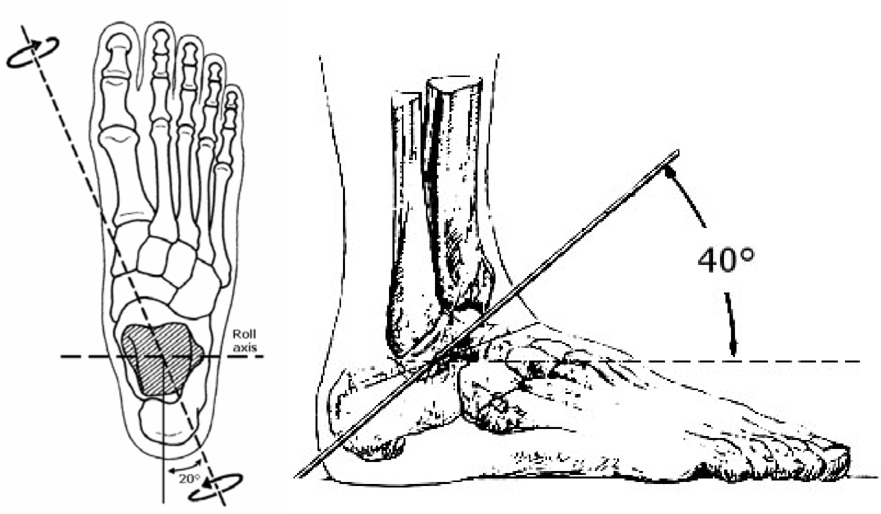

Fig. 1. Orientation of ankle roll axis in humans. Roll axis is rotated 20 degrees toward inner foot side (counter clockwise in transverse plane) and 40 degrees clockwise in sagittal plane.

Multi-segment robot foot needs to satisfy following demands:

- Shape and size of the robot foot should be similar to the shape and size of the adult's human foot,
- Ankle should have 2 DOF joint,
- Fingers need to be actuated,
- Weight of the foot need to be similar to the weight of the adult human foot.

Due to small space available within foot we decided to displace actuation system and to drive foot by driving wires. We also decide to have three fingers instead of five. The decision to keep separate fingers was motivated by wish to avoid all foot fingers to be a single block, but keep fingers as separate "units", to ensure multiple fingers contact with the ground even in case when foot is inclined.

3 Foot Mechanical Design

The robot foot we designed consists of totally 26 parts (Fig. 2). All parts are made of aluminum except of some sliding parts of joints. Thus, weight of the foot itself (without actuation system) has approximate weight of the adult human's foot. Some of the foot parts are designed in more than one version to investigate influence of different designs on foot functionality. One of such parts is ankle joint where we produced two versions (Fig. 3) with different spatial orientations of joint axes. One solution is with perpendicular ankle axes and other is with ankle axes with spatial orientations similar to those of humans. Joint with housing can be simply replaced with another one without any additional change.

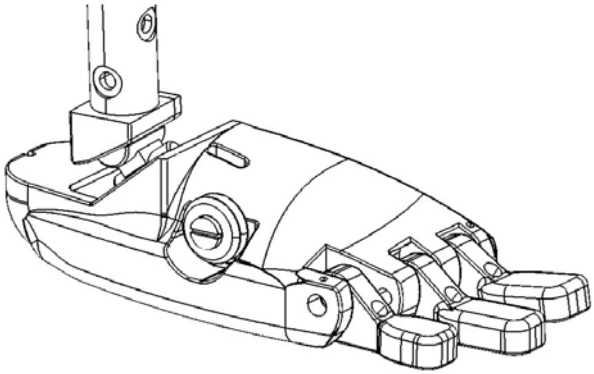

Fig. 2. Picture of the robot foot

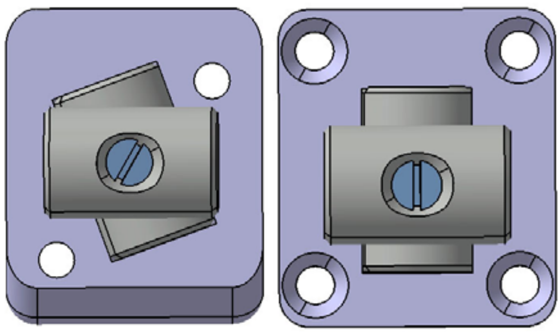

Fig. 3. Two versions of ankle joint that can be used with foot

The foot ankle (Fig. 3) is designed as two sliding cylindrical joints. Rolling bearings are not used to achieve that design would be as compact as possible. Special materials are used for ankle joints to decrease friction between sliding surfaces.

Motion ranges of all joints (ankle and fingers) are same as in humans. Three guide wheels are placed on the foot (Fig. 2) and they will be used for routing fingers driving wires.

4 Actuation

Driving units consisting of a DC motor and a THK LM guide linear actuator will be used for foot actuation (ankle joint). DC motors and a linear actuators shafts are coupled by a timing belts. Therefore, rotational motion of a DC motor is converted to linear motion of the linear actuator's nut block. Due to the high transfer ratio of the linear actuator this system is able to generate high pulling force. Three such driving units will be mounted on each robot's tibia (Fig. 4). Linear actuator's sliding nut will

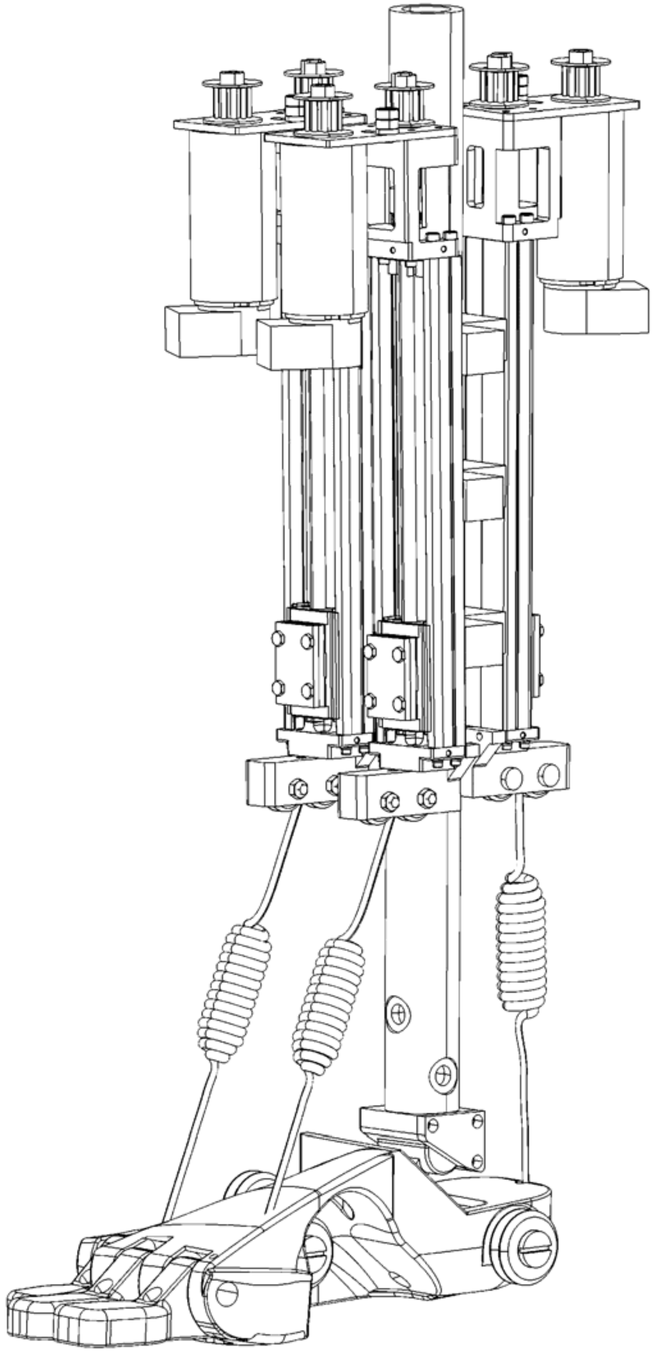

Fig. 4. Robot foot with assembled driving units

be connected with a driving cable to a point on the foot. One driving unit will be used for applying pulling force on the heel and two driving units will be used for applying pulling force on upper front side of the foot. With three driving units it is possible to achieve desired movement in the ankle joints. Using only three driving units has for a consequence slightly complicated control strategy, but weight of the robot leg is significantly reduced. Also, nonlinear springs will be placed on driving wire between linear actuator and the finger in order to introduce elasticity and to enable to control stiffness.

In a first experiments foot fingers will not be actuated. (In Fig. 4 driving wires as well as, actuators for fingers are not shown). Linear springs will be used to introduce elasticity in finger joints. One side of linear springs will be attached on fingers by wires and other side will be connected for tibia by wires too. By bending fingers spring will be extracted. In future experiments intention is to actuate in an active way all tree fingers.

5 Ground Reaction Force Sensing

To enable permanent dynamic balance during walking information about ZMP position is absolutely necessary. By measuring contact pressure between foot and ground or by measuring contact force in several points the ZMP position can be determined[1]. At this moment there are under development several types of sensors appropriate for use at robot foot. They can be classified in two groups: a) miniature, single component sensors which have to be placed at relative large number on the contact surface of the foot (we expect that in this way “profile of the pressure” over foot contact area with the ground can be obtained), and b) bigger sensors which cover larger part of contact foot surface (whole foot may require 3-4 of such sensors). Combination of these two approaches (larger sensors to be placed on foot body, smaller on the fingers) is also possible.

6 Conclusion

In this paper was presented first results of new “human-like” robot foot design. The most of the parts described are already manufactured, but complete assembly and functionality testing has not been performed yet.

We believe the new multi-segment “human-like” robot foot will improve walking capabilities of humanoid robots by achieving better (more vesatile) contact between foot and ground surface. Introducing separate fingers should improve transition from double to single-support phase (push-off phase of gait). As a consequence this will enable more “natural” walking of humanoid robot. We are planning a number of experiments to perform with this foot. We expect the experiments will provide to us additional experience in the course how the design can be further improved.

Our next task will be design of knee and hip joints with appropriate actuation.

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[1] Position of the ZMP is same as position of ground reaction force acting point while robot is dynamically balanced.

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