Designing the test Feet of the Humanoid Robot M-Series

Dusko Lukac
Department of Robotics and Mechatronics
Rheinische Fachhochschule Köln GmbH
University of Applied Sciences
Cologne, Germany
lukac@rfh-koeln.de

Torsten Siedel
Department of Computer Science
Humboldt-Universität zu Berlin
Berlin, Germany
siedel@informatik.hu-berlin.de

Christian Benckendorff
Department of Computer Science
Humboldt-Universität zu Berlin
Berlin, Germany
benckend@informatik.hu-berlin.de

Abstract— **This paper concerns the construction and function of a test foot with a passive toe joint. This was developed within the scope of the EU project ALEAR (Artificial Language Evolution on Autonomous Robots) together with a test leg for the humanoid robot "M-Series" to test different function principles. In particular the sensor types are exemplified which are used in this foot. Further, the sensor principles, the electronic subsequent treatment of the sensor signals as well as their provision for the connected bus system are explained. Concluding, the experiences which were won with the present test construction are highlighted. The outlook is given on the planned foot which should be used in the humanoid "M-Series" robot.**

Keywords: Feet; Humanoid Robots; M-Series; Sensors; Toe Joints

I. INTRODUCTION

A living being is only capable of existence if it can react to environmental influence. Even protozoons have developed this ability. To be able to perform complex motoric tasks like walking it is essential to handle sensory input immediately. In humans this task is accomplished by the spinal cord, which forwards specific sensory information to the brain, but also has neural circuits. This enables the spinal cord to generate reflexes. Hence the brain does not have to care about every single muscle, but cedes this task to the spinal cord. To take up specific stimuli from the surroundings or from the internal, biological structures, which are called receptor, exist. One distinguishes two kinds:

- External receptors

They serve for the orientation in the space and take up stimuli from the environment.

- Internal receptors

They can take up stimuli from the inside of an organism.

The human possesses about 110 receptors. Artificial receptors are referred to as sensors. Inserted in machines, medical and other devices, arrangements, vehicles, coffeemakers and many other products, they provide the ability to react independently to certain states and to inspect this. Sensors transfer the perception property of the person onto machines.

II. BASIC DESIGN OF THE TEST FEET

Figure 1. Photo of the test foot

The foot is designed for a 1.2 meters high humanoid robot and has the dimensions 193mm x 75mm x 25mm. It weighs 230g. The scaffolding of the foot (Figure 1) consists of beveled aluminum tins as well as of plastic parts, which were produced in a rapid prototyping process. The foot is equipped with a passive toe joint loaded with springs. With this construction the possibility exists to improve the rolling characteristics of the foot an also to increase the step length of the leg in later experiments [1] [2]. As sensory feedback three different measurement categories are determined in the foot:

- the ground contact forces in three areas,
- the bending of the toe joint,
- the torque in the toe joint.

All three measured variables are registered using a indirect measuring procedure.

A. Mechanical function of the force measuring assembly

Three force sensors integrated into the foot, are placed within the toe area, in the metatarsus and in the heel (see Figure 2). All three are placed in a line parallel to the sagittal plane and register no lateral forces by this arrangement. This property results from the fact that the test leg with a mounted foot is equipped with a reduced number of degrees of freedom (DOF). These permit merely movements in the sagittal plane. As a result, registering of load differences in the lateral is not relevant to the present test construction.

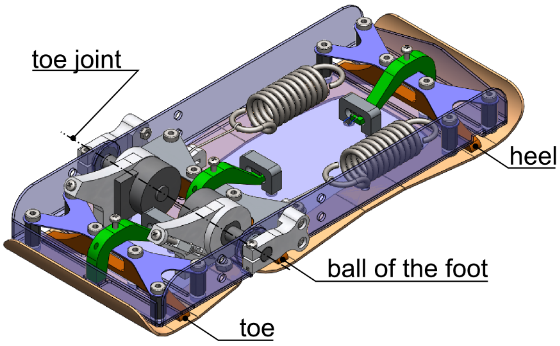

Figure 2. Position of the force sensors and of the toe joint in the foot

Every force measuring device (see Figure 3) is equally constructed and has the following tasks:

- It redirects the force on the sensor, independently of the point of application of the force on the measuring area.
- It transmits the perpendicular part of the force vector on the sensor.
- Weaken of the ground contact force on the measuring range of the sensor.

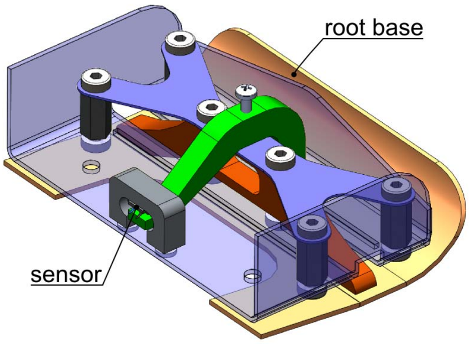

Figure 3. Representation of a single force measuring device

In addition, the offset force of the sensor can be calibrated using an adjusting screw (see Figure 4). This setting possibility is important especially for the "free from float" property of the different components to each other in the force course. The direct forwarding of the ground contact force F_1 is thereby guaranteed to the sensor. The so called "dead" measuring area is avoided by the adjustable preliminary tension. The force girder (Figure 4, brown) is screwed in the upper and bottom side together with an aluminum metal that admits a slight deflection. This construction admits only one linear, vertical movement of the force girder. Consequently, the perpendicular part of the ground contact force which takes effect on the foot sole will merely be further transmitted.

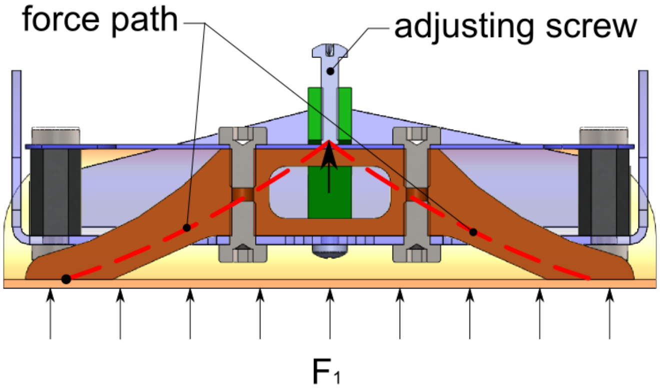

Figure 4. Forces course in the single force measuring device (sectional representation)

The sensor integrated into the force measuring device is designed for a maximum permissible load of 100N. Stepping up and unrolling the foot on the ground can cause the ground contact forces to exceed this value, therefore a lever mechanics (see Figure 5, green) was installed in the strength measuring equipment. This reduces the force effect on the sensor, so that damaging the sensor under strong load is avoided.

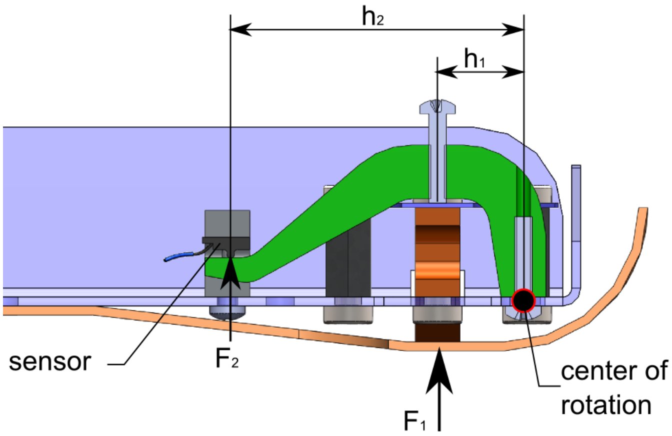

Figure 5. Lateral cut representation of the strength-diminishing lever mechanics

As illustrated in Figure 5, the ground contact force affects the fulcrum on the lever arm in distance h_1. The sensor is in the distance $h_2 > h_1$ to the fulcrum, by which the force F_2 in the sensor is lower than the force F_1. The actually measured force in the sensor is to be calculated using the following formula:

$$F_2 = \frac{F_1 \cdot h_1}{h_2} + F_0 \,. \tag{1}$$

The force F_0 represents the preliminary tension in the unloaded state which can be adjusted through the adjusting screw.

B. *Mechanical function of the toe joint*

The toe joint is connected by two symmetrically placed wire ropes with an extension spring in each case, which are installed in the back part of the foot (see Figure 6). If the toe joint bends itself under load, the connected extension springs are extended. By the bending of the counteracting spring tension, the torque on the toes axis rises, after the Hooke's law, linearly to the bending. By using the preload screw, the length l_1 of the extension spring and thus, the inertial torque of the toe joint can be adjusted. As soon as this inertial torque is exceeded, a bending of the toe joint takes place.

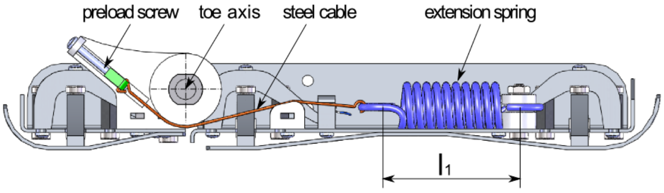

Figure 6. Extension spring system of the toe joint (Lateral cut representation of the foot)

To measure the bending of the toe joint two rotary encoders are integrated coaxially to the rotation axis of the toe joint. The signals of both rotary encoders are summarized to increase the quality of the sensor signal.

With the data of the corner α_z of the toe joint, the unrolling radius r, the spring rate k of the tension spring, the basic length l0 of the unloaded spring as well as the preliminary tension length l1 of the spring, which is adjustable by the pre turnbuckle, the torque of the toes joint can be determined by the following formula:

$$M = k \cdot r\left(l_0 + l_2 - l_1\right) \tag{2}$$

$$M = k \cdot r\left(l_0 + \frac{2 \cdot r \cdot \pi \cdot \alpha_z}{360°}\right) \tag{3}$$

To change the upward gradient of the linear torque identity line, the possibility exists to install tension springs with different spring rates. Through this, e.g., the unrolling characteristic can be adapted to the walking property and the load of the foot.

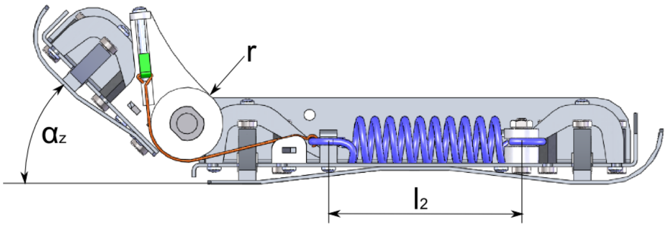

Figure 7. Lateral cut representation of the foot with unrolling of the toe joint

III. SENSORS FOR THE CAPTURE OF MECHANICAL DIMENSIONS

Primarily, length, corner, force, torque and masses (weight force) belong to the mechanical dimensions. Their knowledge is essential for the functionality of machines and procedures. The force is a basic size of the mechanics and can usually not be measured directly. If one arranges a distortion body in the force flow, then from its change the amount of the force can be inferred.. The same principle can be used for estimating the torque. In this case a distortion body under load changes the angle of torsion which can be taken here as a size of a torque. The force moment sensors (force/torque sensors) require an especially decorated distortion body and are always tactile sensors. The scanning happens often with stretch measuring stripe (strain gauges) [3].

A. *Measurements of the forces*

The electric measurement of forces and torques in the mechanical engineering and plant construction, in test states and test benches, with automatic mounting and for the monitoring of impulses is an important task. Regarding the torque sensors, a free ratability of that part of the sensor which lies in the moment flow is usually demanded [4]. Relating to the mode of operation [5] one can distinguish three forms:

- Direct procedures - the mechanical charge affects a magnetically or electrically active body which reacts with a change of his properties.
- Indirect procedures - the mechanical charge generates a counter reaction in a purely mechanical way in a distortion body. A strolling organ registers the changes and transforms them in an electric property.
- Compensation measuring procedures - under load a counter reaction is generated by purely electric or magnetic mechanisms. The procedure can be applied only for small nominal forces or nominal moments.

B. *Sensors in M-Series Humanoid Robot*

In many sensor solutions a distortion body (ductile body) becomes gauged, e.g., smallest stretches or buckling under charge is scanned. In our case we used so called faraday capacitors. The capacity change is grasped by the force effect by the change of the dielectric and the force is measured therefore with the indirect procedure. Because the condenser is bounded with conductive material which creates a Faraday cage, it is insensible to the electromagnetic influence. Therefore the smallest force changes can be very exactly grasped with this sensor.

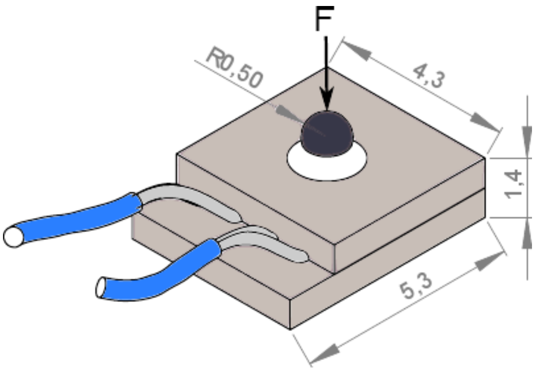

Figure 8. Faraday capacitors (all dimensions in mm)

For the torque measurement an easy procedure is used. The measurement is carried out with potentiometers. Potentiometers consist of a resistance road which is scanned by a grinder. Contact free forms exist as well (leading plastic potentiometer). The position of the tap represents a setting which is proportional to a certain voltage.. The resistance road can be a wire winding, a leading-capable plastic or a metal shift sprayed on a bearer. The road can be even or circular.

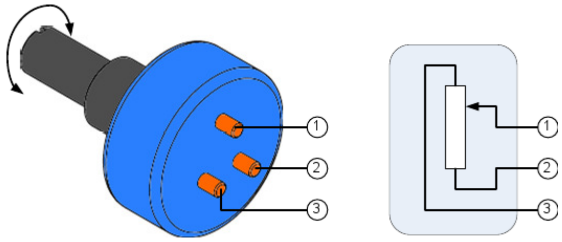

Figure 9. Principle constructions of a potentiometer

The position of the grinder defines a certain length. The position can be determined using the partial resistance value. With the potentiometer without contact a measuring probe above a linear resistance road and a low resistance collector road is moved. Thereby, the measuring signal is capacitively uncoupled. The leading plastic potentiometers (conductive plastic potentiometer) have very interesting properties. They are inexpensive, robust, precise and robust against environmental leverage. Therefore, they are also used in the astronautics, e.g., with the Cassini Huygens mission. There are two types: rotatory and linear. Round potentiometers on leading plastic basis are designed as a double potentiometer with two, 180° rotated and in an opposite direction working resistance roads. Thus, full rotations can be fully detected, because the usual dead zone is covered between beginning and end of the resistance road. In those cases, one can use potentiometers, e.g., in position axes and robot joint axes as in our case [6].

IV. ELECTRONIC LAYOUT

The low-level sensorimotor control tasks will be performed on self-developed, small circuit boards, called AccelBoard3D, which are currently in verification stage. They will be able to accomplish the tasks described below. A STM32F103CBT6 microcontroller by STMicroelectronics is working on these boards. Additionally a 3-axis linear accelerometer is soldered onto them.

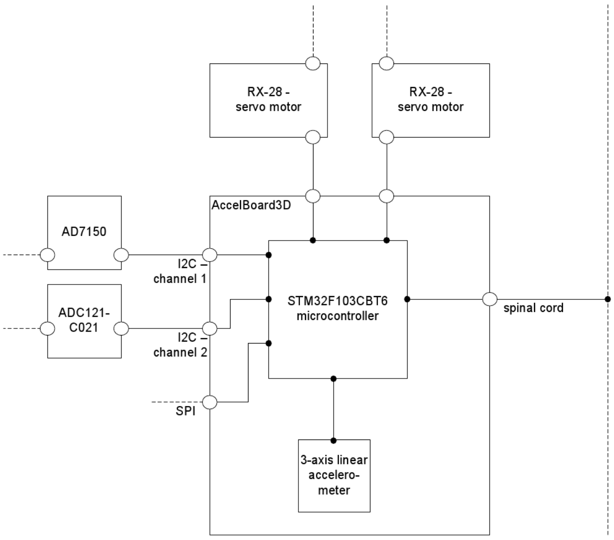

Figure 10. Electronic layout the AccelBoard3D and external components

Lots of those boards will be distributed over the entire humanoid robot, including the feet. They are also responsible for driving all servo motors and for addressing the external sensor IC's, like the AD7150 and the ADC121C021. Furthermore, all AccelBoard3D are communicating with each other and with a high-level processing unit. This communication is similar to the human spinal cord. The robotic spinal cord is realised by the connected AccelBoards. The connection is done through a RS485 bus, for every new cycle the sensory data of all AccelBoards are transferred. Hence, every low- and high-level unit has up-to-date information about the measured values and thus can react immediately to them. One cycle is exactly 10 ms. External devices can be connected via two discrete I2C-bus channels or one SPI-interface. The benefit from two I2C-channels is that it is possible to interface devices with the same address. Both used chips measuring capacity or resistance have an update rate equal or greater than 100 Hz, so that an actual value is available within the 10 ms interval.

V. MEASURING PRINCIPLE

The Faraday-force sensor is evaluated by means of integral circle AD7150. The AD7150 is a signal processing solution for capacitive proximity sensor. The AD7150 uses the capacity and digital converter technology to the combination of characteristics which are important for the coupling in sensors. The integrated adaptive threshold algorithm compensates differences in the sensor capacity which accounts for environmental factors. The following picture shows possible hardware design consideration:

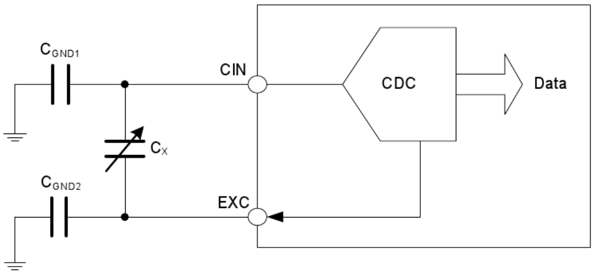

Figure 11. AD7150 hardware design. Source [7]

The Faraday-force sensor (CX) is on the input side connected directly between the EXC and CIN pins. The Faraday-force sensor has very low parasitic resistance and capacitance, so that the affection of the system performance is negligible. The architecture of the capacitance-to-digital converter (CDC) measures the capacitance of the Faraday-force sensor connected between the EXC pin and the CIN pin. According to theoretical considerations [7] “any capacitance CGND to ground should not affect the CDC result” but in the practical application, the result is gradually affected by capacitance to ground. The AD7150 works on the output side as standalone device, “using the power-up default register settings and flagging the result on digital outputs” [7]. In our case AD7150 is connected over I^2C bus to a microcontroller via the 2-wire serial interface, offering flexibility by overwriting the AD7150 register values from the host with a user-specific setup. The following picture shows possible hardware design consideration:

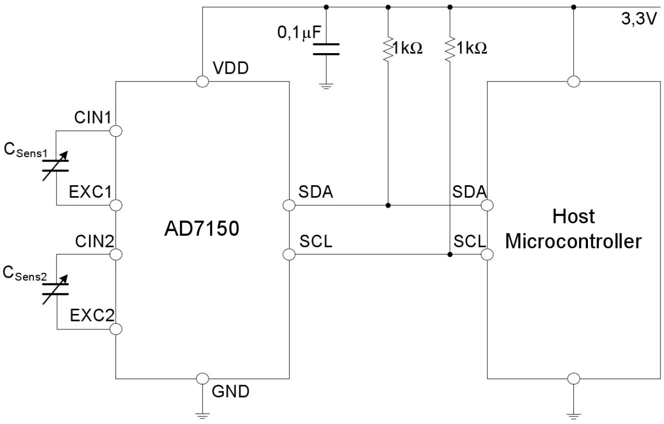

Figure 12. Possible application design. Source [7]

For the measurement of the voltage value in the potentiometer, the analog to-digital converter is used. As an analog to digital converter, the ADC121C021 is used. It is a low power, 12 bits, analog to-digital converter with alert function. The following picture shows possible hardware design considerations:

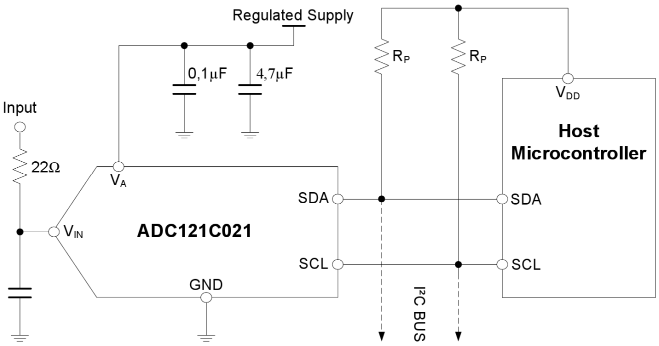

Figure 13. ADC121C021 hardware design. Source [8]

ADC121C021has also I^2C connection possibility and is compatible therefore with the other integral circle and fits into the total electronic concept.

VI. CONCLUSIONS AND FURTHER DEVELOPMENTS

The human foot has the ability to use numerous receptors in order to perceive different loads. At the same time these stimuli must be available for the neural subsequent treatment without appreciable temporal delay. Otherwise dynamic and reactive moving of a human person would be impossible. In this paper we have introduced the mechanical and electronic design of a test foot which was developed for two legged running, together with a test leg, for the humanoid robot of the "M-Series". This development has been developed in support of the biological model – the human foot – as well as after our own experiences and conceivabilities within the scope of the EU project ALEAR. The designed foot represents, in consideration of his extensive properties and compared to similar systems, a low-cost and high-performance solution. The next generation of the foot (see Figure 14) is currently being developed. The foot is weight-optimized and disposes the ability, in contrast to the model introduced in this paper, to register the differences in the ground contact forces along head-on level (see Figure 4). This foot should be used in the humanoid robot of the M-Series, which is in development as well.

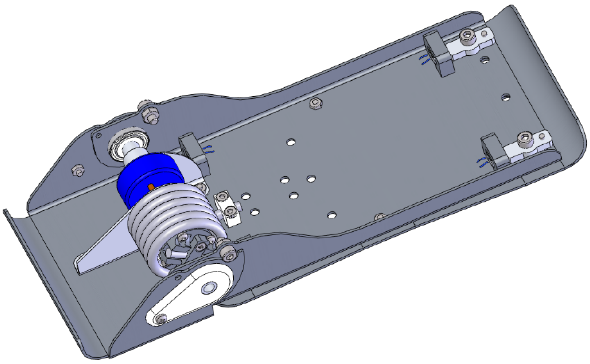

Figure 14. Representation of the succession model

REFERENCES

[1] R. Sellaouti, O. Stasse, S. Kajita and K. Yokoi, “Faster and smoother walking of humanoid HRP-2 with passive toe joints”, IEEE/RSJ International Conferenc on Intelligent Robots and Systems, Beijing, China, 2006

[2] G. Gini, U. Scarfogliero and M. Folgheraiter, “Human-oriented biped Robot design: Insights into the Development of a truly antropomorphic leg”, IEEE International Conferenc on Robotikcs and Automation, Roma, Italiy, 2007

[3] Hesse, S and Schnell, G (2008), Sensoren für die Prozess- und Fabrikautomation Funktion - Ausführung - Anwendung, Wiesebanden, Vieweg Publishing

[4] Bernstein, H (1998), Sensoren und Messelektronik, München, Bad Kissingen, Berlin, Düsseldorf, Heidelberg, Richard Pflaum Publishing

[5] Herold, H (1993), Sensortechnik: Sensorwirkprinzipien und Sensorsysteme, Heidelberg, Hüthig Publishing

[6] Hollerbach, JM (1987), ``Robot hands and tactile sensing," in: AI in the 1980s and Beyond: An MIT Perspective, Grimson, WEL and Patil, RS eds., MIT Press, Cambridge, Mass., pp. 317-342.

[7] Analog Devices (2007) “AD7150, Ultra-Low Power, 2-Channel, Capacitance Converter for Proximity Sensing”, Data Sheet, http://www.analog.com/static/imported-files/Data_Sheets/AD7150.pdf

[8] National Semiconductor (2008) “ADC121C021/ADC121C027 - I2C-Compatible, 12-Bit Analog-to-Digital Converter (ADC) with Alert Function”, Data Sheet, www.national.com/ds/DC/ADC121C021.pdf