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# Design and control of the humanoid robot SURALP

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## Abstract

*SURALP is a 29 degrees-of-freedom full-body walking humanoid robot designed and constructed at Sabanci University - Turkey. The human-sized robot is actuated by DC motors, belt and pulley systems and Harmonic Drive reduction gears. The sensory equipment consists of joint encoders, force/torque sensors, inertial measurement systems and cameras. The control hardware is based on a dSpace digital signal processor. This paper reviews the design of this robot and presents experimental walking results. A posture zeroing procedure is followed after manual zeroing of the robot joints. Controllers for landing impact reduction, early landing trajectory modification, foot-ground orientation compliance, body inclination and Zero Moment Point (ZMP) regulation, and independent joint position controllers are used in zeroing and walking. A smooth walking trajectory is employed. Experimental results indicate that the reference generation and control algorithms are successful in achieving a stable and continuous walk.*

**Key Words:** *Humanoid robot, biped robot walking reference generation*

## 1. Introduction

The bipedal kinematic arrangement can avoid typical obstacles and operate systems in the human environment. This is one of the important motivations for the recent intensive research on humanoid robotics [1, 2, 3, 4, 5]. One of the most challenging problems in this field is the robust balance of the walk. In the control of the bipedal walk complications are caused by the nonlinear and hard-to-stabilize dynamics of the free-fall robot and the coupling effects between the many degrees of freedom [6, 7].

In 2001, Sabanci University, Turkey initiated research on bipedal walking. Experimental phase of this work started in 2006 in the framework of a project funded by TUBITAK. The research targets are bipedal walking on uneven surfaces and manipulation by virtue of visually-aided force control. A human sized full body

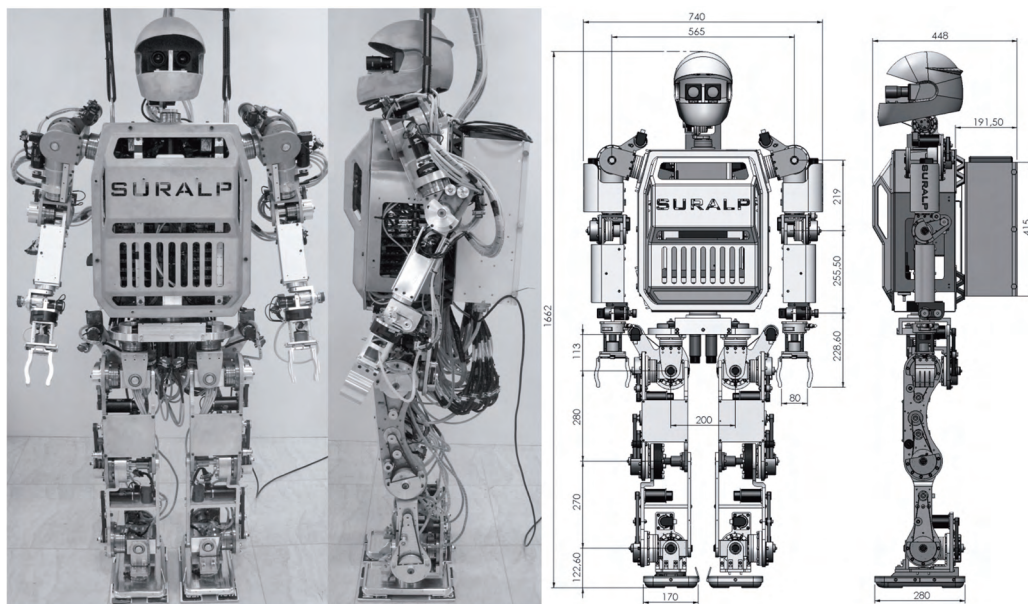
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humanoid robot, SURALP (Sabanci University Robotics ReseArch Laboratory Platform) is designed as the test platform in this project. SURALP is a robot with 29-DOF, with leg, arm, neck and waist joints. The 12 DOF leg module was introduced in [8]. Walking results with the 29-DOF robot platform are presented in [9]. This paper reviews the full body robot SURALP from the mechanical design, sensor and control system aspects. Experimental results are presented too.

## 2. Mechanical design and hardware

The humanoid robot SURALP is shown in Figure 1. It is designed in human proportions. Hips are composed of three orthogonal joint axes intersecting each other at a common point. In the kinematic arrangement, the knee axis follows the hip pitch axis. The ankle accommodates two orthogonal axes: ankle pitch and ankle roll. There is a waist yaw axis positioned on the pelvis. The shoulder motion is realized by three orthogonal joint axes. These axes are followed by a revolute elbow joint. A roll and a pitch axis positioned in the forearm actuate the wrist. The neck has a pan-tilt structure.



**Figure 1.** SURALP, side and front views.

After the preliminary mechanical design, simulation studies are carried out in a Newton-Euler method based full-dynamics 3D simulation and animation environment as described in [10] in order to determine link strength and motor capacity requirements. Finite element analysis is carried out with the data obtained in the simulations. DC motors, Harmonic Drive and belt-pulley systems are used to drive the joints. The sensor system of SURALP includes encoders measuring the motor angular positions, force and torque sensors at the wrists and ankles, inertial sensors and cameras. The control electronics is based on dSpace modular hardware. A DS1005 board of the dSpace family is central in our controller which is hosted by a Tandem AutoBox enclosure mounted in a backpack configuration.

### 3. Control algorithm

The joint position references are generated through inverse kinematics from Cartesian foot references defined in world frame coordinates shown in Figure 2. The reference trajectories in this figure are obtained to fulfill periodicity requirements. The  $x$ -direction references are chosen as smooth curves which remain at constant values when the two feet are on the ground. The  $y$ -direction foot references move the body away from the swing foot in order to enhance the balance of the robot. The feet are kept always parallel to the body. The joint position references are obtained via inverse kinematics from the Cartesian foot trajectories and joint position control is achieved by PID controllers. A number of additional control techniques are used to change the position references in the Cartesian space or joint level position references with feedback from force/torque transducers and inertial sensors to achieve stable walking. Below, these additional controllers are outlined.

*Foot orientation control:* The scheme computes joint angle reference modifications such that the feet are parallel to the ground when they are in contact with the ground [3]. For the ankle roll axis, the following reference modification law is employed.

$$\bar{\Theta}_{roll}(s) = \Theta_{roll}(s) + \frac{K_{roll}}{s + \lambda_{roll}} T_{roll}(s) \quad (1)$$

Here  $s$  is the Laplace variable.  $\Theta_{roll}$  is the roll joint reference angle.  $\bar{\Theta}_{roll}$  is the reference angle after the reference modification,  $T_{roll}$  is the torque about the roll axis due to the foot-ground interaction.  $K_{roll}$  and  $\lambda_{roll}$  are low pass filter constants.

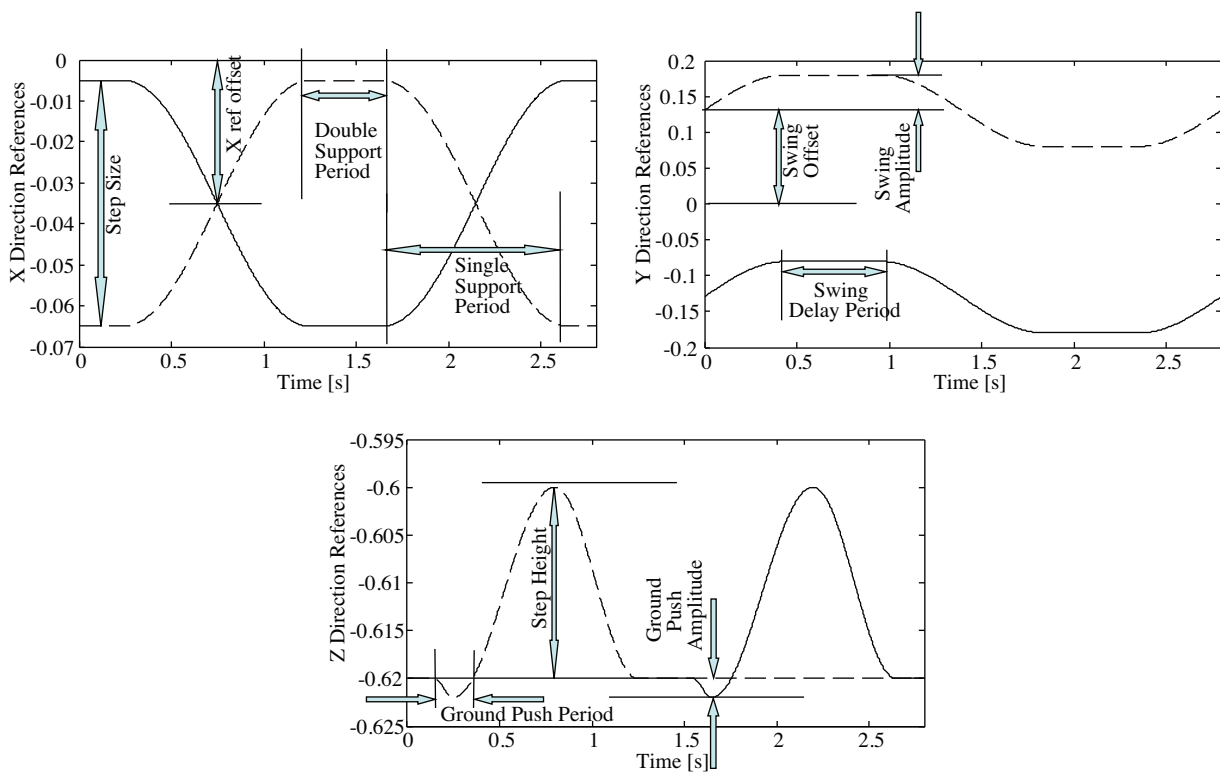
*Ground impact compensation:* Another problem in achieving stable walking is the foot landing impact [4]. We employed a second order relation to modify the distance between the hip and sole of the landing foot in order to insert a virtual mass-spring-damper system between the hip and ankle as a shock absorber.

$$\bar{l}(s) = l(s) - \frac{1}{m_l s^2 + b_l s + k_l} F_z(s) \quad (2)$$

Here,  $l$  represents the hip-to-sole distance reference obtained from Cartesian foot reference trajectories.  $\bar{l}$  is its shock absorber modified version.  $F_z$  is the  $z$ -direction component of the ground interaction force acting on the foot.  $m_l$ ,  $b_l$  and  $k_l$  are the desired mass, damping and stiffness parameters of the mechanical impedance relation.

*Early landing modification:* One of the main problems of early landing of a swung foot is that when it is on the ground before the planned beginning of the double support phase, it will go on moving forward. As a result, the feet will slip and the robot will possibly lose its balance. In order to avoid such a condition, the  $x$  direction references in Figure 2 are modified in the case of an early landing. Specifically, this modification "stops" the  $x$  direction references of the feet at their values they had at the instant of early landing. These references are kept fixed until the next walking cycle.

*Trunk orientation control:* In order to keep the trunk vertically aligned simultaneous control of effective leg lengths and ankle pitch/roll angles is carried out. In the sagittal direction part of this controller the ankle pitch angles are modified by using feedback from body inclination. The control law employed is



**Figure 2.** Cartesian reference trajectories for the feet as expressed in a coordinate frame attached to the trunk. (Solid curves: Right leg. Dashed curves: Left leg)

$$\bar{\Theta}_{pitch}(s) = \Theta_{pitch}(s) + (K_{P-pitch} + K_{I-pitch} \frac{1}{s}) \Theta_{trunk\ pitch}(s) \quad (3)$$

where  $\Theta_{pitch}(s)$  is the pre-planned pitch angle reference for the ankle joints and  $\bar{\Theta}_{pitch}(s)$  is the modified reference.  $\Theta_{trunk\ pitch}(s)$  is the trunk pitch angle measured by the inclinometer.  $K_{P-pitch}$  and  $K_{I-pitch}$  are controller gains, respectively. The trunk roll angle control is carried out by using the effective leg lengths:

$$\begin{aligned} \bar{l}_{left}(s) &= l_{left}(s) + (K_{P-roll} + K_{I-roll} \frac{1}{s}) \Theta_{trunk\ roll}(s) \\ \bar{l}_{right}(s) &= l_{right}(s) - (K_{P-roll} + K_{I-roll} \frac{1}{s}) \Theta_{trunk\ roll}(s) \end{aligned} \quad (4)$$

In Eqn. (4),  $l_{left}$  and  $l_{right}$  are the pre-planned effective lengths of the left and right leg, respectively.  $\bar{l}_{left}$  and  $\bar{l}_{right}$  are their versions after the application of the trunk orientation controller.  $K_{P-roll}$ ,  $K_{I-roll}$  and  $\Theta_{trunk\ roll}$  are controller gains and is the measured trunk roll angle.

*ZMP regulation:* In this paper, we employed ZMP control for the homing (zeroing) process of the robot. For this purpose, a simple proportional action relation between the ZMP error and pelvis horizontal position

proved to be successful. The ZMP reference for zeroing the robot is defined in the middle of the supporting polygon.

$$\bar{X}_{ref\ offset}(s) = X_{ref\ offset}(s) + K_{P-ZMP\ X}(X_{ZMP\ desired}(s) - X_{ZMP\ actual}(s)) \quad (5)$$

$$\bar{Y}_{ref\ offset}(s) = Y_{ref\ offset}(s) + K_{P-ZMP\ Y}(Y_{ZMP\ desired}(s) - Y_{ZMP\ actual}(s)) \quad (6)$$

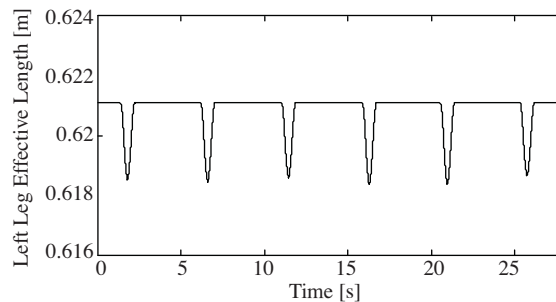
$X_{ref\ offset}$  and  $Y_{ref\ offset}$  are the center locations of the Cartesian reference trajectories shown in Figure 4.  $\bar{X}_{ref\ offset}$  and  $\bar{Y}_{ref\ offset}$  are their modified versions. Another control activity is the application of a waist joint trajectory to counteract the motion of the swing foot. When the left foot moves forward, the right shoulder is moved forward with a rotation of the waist joint. A similar motion takes place with the left foot and right shoulder too. Also the body is kept "bent" with a small angle called "body pitch angle" with respect to the ground as a result of combined motion of the leg joints. This angle moves the center of mass of the body forward and creates a counterweight in order to compensate the weight of the controller in the back pack configuration.

## 4. Experimental results

The controllers discussed in Section 3 are employed for walking experiments with SURALP. The various control and reference generation parameters are obtained by trial and error. Table 1 shows these parameters. The comparison of the original and the modified ankle roll angle references shows the effect of the foot orientation control. Ankle pitch angle references are modified in a way similar shown in this figure too. The modification of the hip-to-sole distance of the right leg by the ground impact compensation is shown in Figure 3. The stability of the walk is verified by the smoothness and the repeatability of the modification of the hip-to-sole distance.

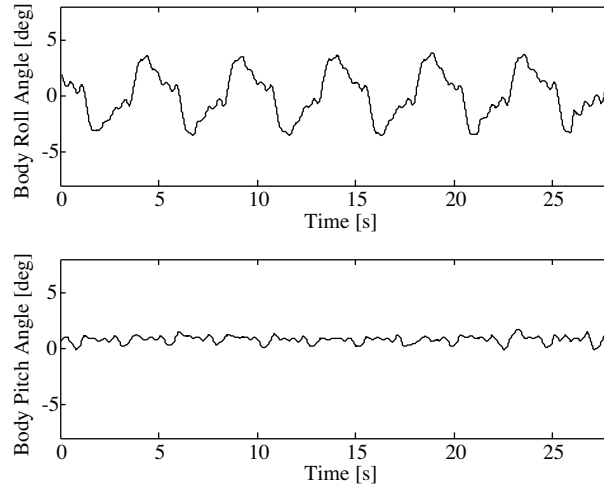
**Table 1.** Reference trajectory generation parameters.

Single Support Period	1.1s	Step Size	0.05m
Double Support Period	1.2s	Ground Push Amplitude	0.013m
Ground Push Period	0.8s	Swing Amplitude	0.06m
Swing Delay	0.5s	Swing Offset	0.14m
Step Period	4.6s	Body Height	0.62m
Step Height	0.007m	X reference offset	-0.065m
Body Pitch Angle	3deg	Waist Motion Amplitude	6.3deg



**Figure 3.** Hip-to-sole distance modifications of the left leg.

The trunk roll and pitch angle oscillations during the walk are measured by the inclinometer located on the trunk of the robot and shown in Figure 4. They indicate the steady nature of the walk obtained by the use of the control system too. Other controllers produced steady regimes of control actions too.



**Figure 4.** Robot body roll and pitch angle oscillations.

## 5. Conclusion

The humanoid robotics experimental platform SURALP is described in this paper. Mechanical design principles, actuators, sensors and control hardware are reviewed. A smooth walking reference generation method and force/torque transducer and inertial sensor feedback based controllers for SURALP are outlined. A stable walk is achieved by the designed control methods. Experimental results indicate that the robot system is a suitable test bed for humanoid robotics research. This is the main contribution of the studies reported in this paper. Zero Moment Point stability criterion based walking trajectory generation and its application to the robot is the next stage of the studies. Also, walking on uneven surfaces and environmental interaction with the upper body motion is planned as active research directions.

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