Design of a Library of Motion Functions for a Humanoid Robot for a Football Game

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Abstract— **Humanoid robots are enjoying increasing popularity as a research tool and education tool. The ultimate goal of the international RoboCup Initiative is to build a humanoid soccer team which beats a human World Cup Champion team in 2050. Despite impressive achievements of some teams, the overall performance of the soccer playing humanoids is still far from perfect. The robots sometimes show instability while walking, fail to kick the ball or defend against shots not taken. In this study we present a geometrical model for the walking legs of the Kondo KHR-1 humanoid robot. The model allows to establish the relationships between a set of function walking motion controls and that of the leg controlled angles. Furthermore, we use the German team SimRobot to program the soccer scene and for the analysis of Kondo walking motion. For this we developed a 3D model as part of the SimRobot controller. A set of synthesized walking motions were designed. The result is a library of motions which are: 1) Walking Forward 2) Walking Backwards 3) Step right/left 4) Turn right/left 5) Swat right/left 6) Kick right/left 7) Bow 8) Push-ups. The library is useful to facilitate soccer behavior programming for preparing the students to the RoboCup competition.**

Index Terms— **distributed intelligence, multi-robot cooperation, robocup, simulation, walking.**

I. Introduction

Humanoid robots are enjoying increasing popularity as a research tool. More and more groups worldwide work on issues like humanoid bipedal motion, audio-visual perception, human-robot interaction, and learning, targeted for the application in humanoid robots. These efforts are motivated by the vision to create a new kind of tool: robots that work in close cooperation with humans in the same environment. The ultimate goal of the RoboCup Initiative is to build a humanoid soccer team which beats a human World Cup Champion team. The reasons why this goal should be pursued are described in [1]. Analysis of technical issues involved in humanoid to play soccer game are also presented. The analysis demonstrates the breadth of technologies need to be developed through the course of the Challenge, which has major impacts to industries in general.

To analyze the walking motion a simulator [2] for Open Dynamics Engine (ODE) for humanoid motion control allows controlling the rigid body dynamics, joints between rigid bodies, collision, and friction. The simulator supports polygon data format (STL) which editing the (1) the data position, rotation, and zoom, (2) the robot pose through angles, (3) setting of the pose transition times. The joint angle values are linearly interpolated between poses. Calculation of the robot center of gravity and zero momentum point help a gyro sensor to improve motion stability. The linear inverted pendulum is used to generate the motion pattern which provide a motion profiler which is subdivided into eight points and trajectory is approximated between points by linear interpolation.

A sensory-based biped walking motion instruction system [3] uses visual and auditory sensors to generate walking patterns according to human orders. The motion of lower-limbs for locomotion is created by an online pattern generator based on the sensory information. At the same time, the motion of the trunk and the waist for stability is generated online by a balance control method. Combining these locomotive and balance motions, a complete walking pattern is hierarchically constructed and memorized on a database. The walking is conducted through simulations. The behavior learning method based on Bayesian Networks which provide a behavior learning method without the need for any prior knowledge of the robot. A complete walking cycle consists of stationary, transient, steady, transient and stationary phases.

The biped robot control [4] and walking pattern generation can be based on the knowledge of(1) accurate robot dynamics to determine the zero-moment point for pattern generation and walking control, (2) uses feedback control and the inverted pendulum approach. A walking pattern generation method is proposed to allow arbitrary foot placements as a mixture of the ZMP based and the inverted pendulum based approaches. It is shown that by using the preview controller, we can take into account the precise multi body dynamics even though the method is based on a simple inverted pendulum model. Walking pattern generation for given a ZMP can be solved as the different three problems: 1) Pattern generation as an inverse problem 2) ZMP control as a servo problem 3) Pattern generation by preview control A robot can be represented as a cart in the cart-table model and plot the cart motion as the trajectory of the center of mass (CoM) of the robot, which allows for an easy calculation of the ZMP by using the ZMP equations.

Analysis of dynamic consistency in the generation of human-like motion for robots may target energy optimization [5]. A mechanism to recognize and generate human-like motions, such as walking and kicking, for a humanoid robot using a simple model based on observation and analysis of human motion. The goal is to establish a design principle of a controller in order to achieve natural human-like motions.

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Simulation results show that faster and more accurate searching can be achieved to generate efficient human-like gait. In comparison with methods that do not include observation of human gait. The gait has been successfully used to control Robo-Erectus, a soccer-playing humanoid robot, which is one of the foremost leading soccer-playing humanoid robots in the RoboCup Humanoid League.

A HiFi 3D simulation platform [6] for humanoid robot is proposed for the simulation of accurate physics model, realistic 3D collision effect, and real-time decision-making. The simulator consists of a server module, client module and debugger module. Its main functions include the 3D/2D real-time display, strategy-loader, human-computer interaction and intelligent referee. The proposed simulation platform for humanoid robot soccer is validated as a simulator with high accuracy and high fidelity.

The online generation of trajectories for omnidirectional walking on two legs is presented in [7]. The gait can be parameterized using walking direction, walking speed, and rotational speed. Our approach has a low computational complexity and can be implemented on small onboard computers. The proposed approach was tested using a humanoid robot Jupp. The competitions in the RoboCup soccer domain showed that omnidirectional walking has advantages when acting in dynamic environments.

Multirobot cooperation[8] during has been addressed for passing the ball from one robot to another, receiving the ball and kicking, and handling exceptions invoke teamwork between two robots which know from each other that they are committed to a relational behavior. The joint commitment is established based on a finite state machine and a messaging system to: (1) synchronize the pass behavior, (2) reiterate the process and extend the pass to another partner, or (3) break the commitment and search for a new partner depending on dynamic game conditions.

Despite impressive achievements of some teams, the overall performance of the soccer playing humanoids is still far from perfect. Basic soccer skills, such as robust walking and kicking without loosing balance are not possessed by all robots. Even the best robots sometimes show instability while walking, fail to kick the ball or defend against shots not taken. Consequently, further research is needed. Within the Humanoid League, the performance of smaller, servo-driven robots in general exceeded the performance of larger robots. On the other hand, the availability of low-cost robot bases, like RoboSapien, and construction kits, like Kondo KHR-1, makes it possible to enter the humanoid league competitions without the need for huge resources. This paper presents a library of motion functions for Kondo, the options available and the approach that was taken along with a discussion of problems met and the mathematical model developed. The Kondo is a Humanoid Robot Kit suitable for teaching robotics at the senior level for participation in the RoboCup competition. The robot is used for a senior course for preparing the student for the RoboCup competition at the Computer Engineering Department at KFUPM.

The organization of this paper is as follows. In Section 2 the A geometrical model for the Kondo Leg is presented. In Section 3 the description of experimental tasks is presented. In Section 4 the walking motion simulation using SimRobot is presented. In Section 5 the implementation of the library of Motion Functions is presented. We conclude in Section 6.

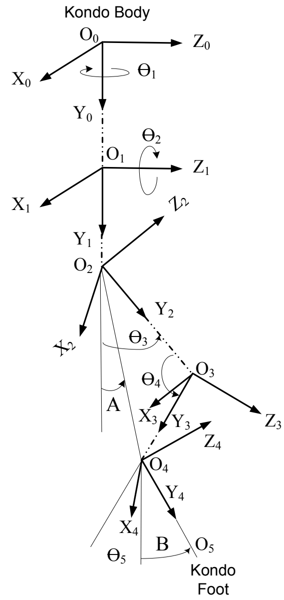

Fig. 1. The Kondo leg is geometrically modeled as a sequence of six serial frames $R_i\{O_i, X_i, Y_i, Z_i\}$ with origin O_i, and X_i, Y_i, and Z_i are the frame unit vectors. The leg is a chain of points $O_0 - O_1 - O_2 - O_3 - O_4 - O_5 - O_6$.

II. A GEOMETRICAL MODEL FOR THE KONDO LEG

The KHR-1HV is a Humanoid Robot Kit suitable for teaching robotics at the senior level for promoting student participation in the RoboCup competition at the Computer Engineering Department at KFUPM.. The robot has 6 dofs (motors) for each leg, and 3 dofs for each arm, and one dof motor for its head. It has a servo-controller and software to allow simultaneous control of all of its 19 dofs where is actuated by a separate motor. The robot height is 35.3 cm and its weight 1.270 Kgrs.

In order to describe the position and orientation of the robot leg in space a frame of reference is attached to each link. The frame of reference is defined using three orthogonal vectors $\{X, Y, Z\}$ as show in Figure 2 for the fixed frame R_0 which is attached to the body of the Kondo. Frame R_1 is subject to rotation with respect to its Z axis, i.e. has a rotation matrix $ROTz$. The geometric structure of the Kondo leg is defined using six revolute joints as $ROTy(\theta_1)$, $ROTz(\theta_2)$, $ROTx(\theta_3)$, $ROTx(\theta_4)$, $ROTx(\theta_5)$, and $ROTz(\theta_6)$, where θ_i represents the angle of the ith dof and O_i is the position of its frame origin. The Kondo foot frame is described by a frame of reference which is observed relative to the base frame R_0 as shown in Figure 2.

A Cartesian coordinate system is defined by introducing three orthogonal vectors X, Y, Z. A frame can be defined by the orthogonal vectors with origin O. We say that the link L_{i+1} revolute with respect to link L_i when frame R_{i+1} rotates relative to either axes X_i, Y_i or Z_i as shown in

Figure ??-(c). The end point O_{i+1} of L_{i+1} can be associated a vector O_iO_{i+1} which will be denoted by $O_iO_{i+1,i}$ to indicate that the vector is observed in frame R_i. $M_i^{i+1} = [X_{i+1,i}, Y_{i+1,i}, Z_{i+1,i}]$ is the transfer matrix from frame R_{i+1} to R_i, which represents the rotation between links L_i and L_{i+1}.

The following notation is used for defining the geometric model for the Kondo KHR-1:

- Every joint is attached to a frame of reference.
- Link L_i is between frame R_{i-1} and frame R_i.
- M_i^{i+1} is used to represent the rotation between links L_i and L_{i+1}
- The orientation matrix $M_0^n = [X_n^0, Y_n^0, Zn^0]$ determines the orientation of foot frame R_n with respect to Kondo body frame R_0.
- The position vector is given by the following expression:

$$O_0O_{i,0} = O_0O_{i-1,0} + M_0^i O_{i-1}O_{i,i} \tag{1}$$

Based on the above, the link vector $O_iO_{i+1,i}$ can be expressed as follows:

$$O_iO_{i+1,i} = M_i^{i+1}.O_iO_{i+1,i+1} \tag{2}$$

where $O_iO_{i+1,i+1}$ denote the vector O_iO_{i+1} observed in frame R_{i+1}. Note that the vector $O_iO_{i+1,i+1}$ has a simple expression because link L_{i+1} is parallel to axis Z_{i+1}. Therefore, the position vector $O_0O_{n,0}$ can be decomposed as the sum of the link vectors:

$$O_0O_{n,0} = \sum_{i=1}^{n} M_0^i.O_{i-1}O_{i,i} \tag{3}$$

vector $O_{i-1}O_{i,i}$ has a simple expression because it is represented with respect to its own frame of reference R_i. Both the vector $O_0O_{i,0}$ and M_0^i can be expressed in a recursive form, leading to:

$$M_0^i = M_0^{i-1}.M_{i-1}^i \tag{4}$$

$$O_0O_{i,0} = O_0O_{i-1,0} + M_0^i.O_{i-1}O_{i,i} \tag{5}$$

where M_0^{i-1} is the transfer matrix from R_0 to R_{i-1}, and M_{i-1}^i is the transfer matrix from R_i to R_{i-1}. The orientation matrix

$$M_0^n = [X_{n,o}, Y_{n,o}, Z_{n,o}] = \begin{pmatrix} X_x & Y_x & Z_x \\ X_y & Y_y & Z_y \\ X_z & Y_z & Z_z \end{pmatrix} \tag{6}$$

is used to determine the orientation of the leg frame R_n with respect to the frame R_0, and the position vector $O_0O_{n,0}$ is used to determine the position of the frame R_n with respect to the frame R_0

We express the length of the vector $[O_2O_{4,1}]$ which has a length E, called the leg extension. To find the expression of $[O_2O_{4,1}]$ we report frame R_1 at origin O_0. Thus $O_0O_{1,0} = 0$. Since the link body L_2 is defined along vector Y_2 of frame R_2. Vector $O_2O_{2,0}$ is obtained using equation A and B:

$$M_0^2 = M_0^1.M_1^2 = M_0^1.ROTz(\theta_2) \tag{7}$$

$$O_0O_{2,0} = O_0O_{1,0} + M_0^2 O_1O_{2,2} \tag{8}$$

Similarly, the orientation matrix M_0^3 and the position vector $O_0O_{3,0}$ can be obtained as:

$$M_0^3 = M_0^2.M_2^3 = M_0^2.ROTx(\theta_3) \tag{9}$$

$$O_0O_{3,0} = O_0O_{2,0} + M_0^3 O_2O_{3,3} \tag{10}$$

Using the above equations, the orientation matrix M_0^4 and the position vector $O_0O_{4,0}$ are:

$$M_0^4 = M_0^3.M_3^4 = M_0^3.ROTx(\theta_4) \tag{11}$$

$$O_0O_{4,0} = O_0O_{3,0} + M_0^4 O_3O_{4,4} \tag{12}$$

It can be easily shown that:

$$O_2O_{4,1} = M_1^0 O_2O_{4,0} = M_1^2 O_2O_{3,2} + M_1^3 O_3O_{4,3} \tag{13}$$

where $M_1^0 = (M_0^1)^{-1}$. After substituting the rotation matrices for the Kondo, we obtain:

$$O_2O_{4,1} = ROTx(\theta_3)O_2O_{3,2} + ROTx(\theta_3 + \theta_4)O_3O_{4,3} \tag{14}$$

This equation simplifies to:

$$O_2O_{4,1} = \begin{pmatrix} 0 \\ C_3l_3 + C34l_4 \\ S_3l_3 + S34l_4 \end{pmatrix} \tag{15}$$

where S_3 (also C_3) and $S34$ denote the sine of θ_3 and that of $\theta_3 + \theta_4$. The length E of the leg extension is $E = [(C_3l_3 + C34l_4)^2 + (S_3l_3 + S34l_4)^2]^{1/2}$:

$$E^2 = (C_3l_3 + C34l_4)^2 + (S_3l_3 + S34l_4)^2 \tag{16}$$

This equation simplifies to:

$$E^2 = l_3^2 + l_4^2 + 2l_3l_4C4 \tag{17}$$

When the kondo leg is controlled using some prescribed values of its extension E, θ_4 will be computed as:

$$\theta_4 = C^{-1}[(E^2 - l_3^2 - l_4^2)/2l_3l_4] \tag{18}$$

This enables us finding angle A (Figure 2) defined between E and the Y_1 axis which represents the direction of E with respect to the leg orientation:

$$E \times SA = C_3l_3 + C34l_4 \tag{19}$$

$$E \times CA = S_3l_3 + S34l_4 \tag{20}$$

By expanding the terms $C34$ and $C34$, simplifying, and solving for CA and SA, we can θ_3 as function of A and θ_3:

$$S3 = \frac{ECA(l_3 + C4l_4) - S3l_4ESA}{l_3^2 + l_4^2 + 2l_3l_4C4} \tag{21}$$

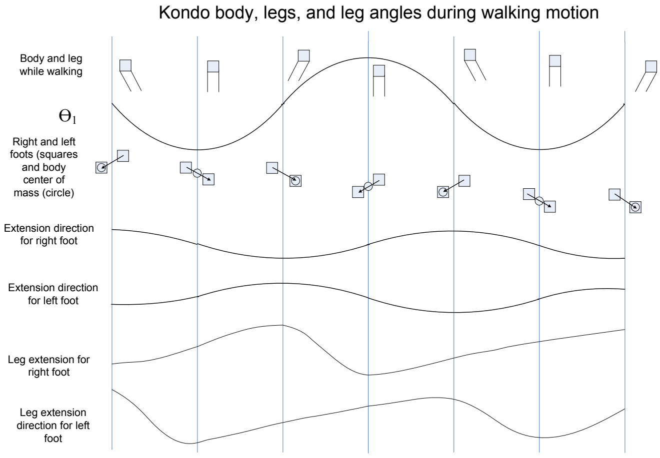

Fig. 2. The leg motion coordination during the walking: (1) the projection of center of mass (circle) is swapping between left and right legs, (2) the direction of the leg extension, and (3) the leg extensions.

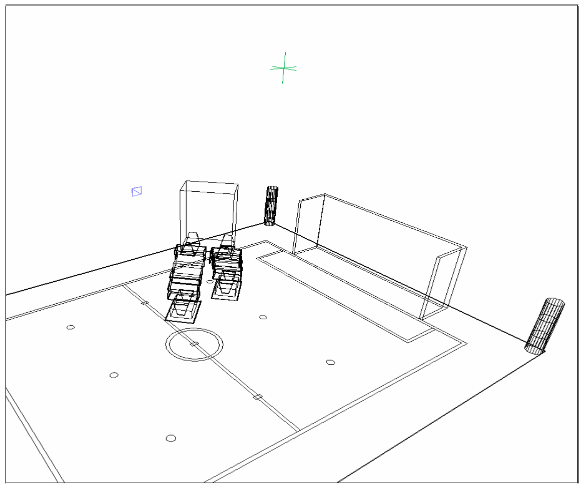

Fig. 3. 3D simulation of Kondo body and legs using Simrobot German team simulator.

$$C3 = \frac{ESA(l_3 + C4l_4) + S3l_4ECA}{l_3^2 + l_4^2 + 2l_3l_4C4} \tag{22}$$

The above two equations allows finding a unique solution for θ_3. The Kondo foot (pose) orientation is denoted by B is Figure 2. It can be easily seen that $B = \theta_3 + \theta_4 + \theta_5$. This gives the solution for θ_5 when a desired value of B is to controlled:

$$\theta_5 = B - \theta_3 - \theta_4 \tag{23}$$

Denote by C the lateral orientation of the kondo foot pose, i.e. $C = \theta_2 + \theta_6$. In order to enforce a foot pose that is parallel to the walking path, we need to have $C = 0$ which allows finding $\theta_6 = -\theta_2$ when θ_2 is independently controlled. Finally θ_1 is used to cause the kondo walking and **turning**. Thus θ_1 is determined independently from all the other Kondo leg angles.

In conclusion, we derived a geometrical model to control the Kondo leg angles based on the knowledge functional parameters which are: (1) θ_1 to control the turning, (2) θ_2 to control the move of center of mass between left and right legs, (3) the leg extension E, (4) A as the direction of E. The presented system geometric model and its inverse allows finding all the Kondo leg angles (θ_1, .., θ_6) based on the knowledge of the above four control parameters.

The leg motion coordination is shown on Figure 2 which describes the functional parameters and how the projection of the center of mass is swapping between the two legs of the kondo humanoid. Row 1 describes the variations of θ_1 for the left and right legs (same) while walking and the plot of θ_1 (row 2). Row 3 shows the projection of the body center of mass when when swapping between the right and left rows. for difference phases of the motion. The extension angles for both left and right legs are shown next. The length of the extension for both left and right legs are shown in last two rows. These plot are used to feed the geometric model with the desired functional parameters. The model (inverting the geometric model) is then used to find the Kondo leg angles. The angles are applied to the Kondo to validate the solution and make any adjustment. Finalized kondo solution can then be used in the design of walking motion.

III. Walking motion simulation using SimRobot

SimRobot is a German simulator [9] for RoboCup. It allows creation of 3D such as the soccer filed and the playing robots. It is a useful tool to develop an educational humanoid robotics. SimRobot can be used with ”Microsoft Visual Studio”. The motion of modeled robot can be controlled using C++ scene's controller code which is user defined. The scene is the description of the WORLD which consists of the soccer field and robots RoboCupSoccer Humanoid for teen size league. For this a standard Controller has been developed with all the Actuators and the Sensors. The 3D model of the soccer field will help students to start developing behavior, localization and image processing using SimRobot.

The Controller takes the data from the sensors from the Scene and processes as described by the user program and computes the commands to be output to the robot actuators. The controller, unlike the scene which takes a special language and compiler, uses a normal C++ code. For this a script has been written and attached to the SimRobot in the IDE and then compiled to activate the controller scene. Having many scenes, SimRobot requires from every controller to be attached to a scene. Using the geometric model develpoed in the previous section, a 3D model of the the Kondo has been developed with the standard soccer field as shown in Figure 3. The simulation allowed the analysis of the library of motion functions. The main benefit is to see the walking motion in a simulated scene and be able to provide some useful feedback on overall Kondo walking motion as a result from assigning the walking trajectory trough the functional parameters described in the previous section. It also allows to experience with soccer behavior programming within the controller design. In this case the controller read the simulated vision sensor, determine the scene seen by the robot, analyze the scene, and determine the next action in terms of moving towards the ball, position behind the ball, turning and facing the opponent goal, and kicking. These activities can be incorporated as part of the controller and run by the students which allow them to see their playing robots.

IV. Implementation

The Kondo HeartToHeart (H2H) is a native serial interface and motion mixer that communicates with the microcontrollerthrough a USB serial adapter. H2H allows has a user friendly GUI which allows recording of a total of 80 motions (30 positions maximum for each motion) and 5 scenarios (e.g. walking than turning left). H2H allows to edit the contents of the microcontroller memory, adjust the gyro sensors and analog input, enter the value of angles for each position manually or by capturing the values after adjusting the robot physically (teaching mode). H2H allows connection the collections of positions and the creation of conditional branches and loops. The library of walking functions is demonstrated using a set of video clips for the Kondo humanoid which can be found at [10].

We used a Laurent Communication Library (Laurent Lessieux) to allow C/C++ developer to communicate with an RCB3 driven robot using the serial link from a PC running under the Windows OS.

H2H operates by (1) selecting and placing a position on the data canvas, (2) change the values of each servo according to the first motion desired, (3) repeat the above step for each position until the motion is complete, (4) place the start flag on the first position in a sequence, (5) connect the sequence of positions. The synthesized motion data structure is saved into the Kondo memory and can be invoked as a motion function by a specific command.

The library of motion functions was developed by compiling the motions and scenarios using the H2H interface, save them on Knodo memory, and invoke them by set of commands whenever necessary. This allows composing complex and accurate motions and scenarios through a variety of means, for example by setting the angle positions for each channel or positioning the robot physically and capturing the values through the teaching mode. Using the above approach we compiled and edited the following library of motions: 1) Walking Forward 2) Walking Backwards 3) Step right/left 4) Turn right/left 5) Swat right/left 6) Kick right/left 7) Bow 8) Push-ups.

As opposed to the use of a walking pattern generator, we used the basic bipedal robot walking principles. For example, the walking forward motion is designed based on: (1) home position is only a point of reference used to compare poses and movements,(2) start and end in a balanced, natural position with the knees slightly bent, (3) use the arms for balance while in motion, (4) shift weight from side to side, (5) lift the feet up off the surface, (6) upper body should remain level and perpendicular to the surface, (7)adjust lower servos to keep the upper body positioning, (8) keep the soles of the feet parallel to the floor surface, (9) Com should stay within the foot/sole balance region.

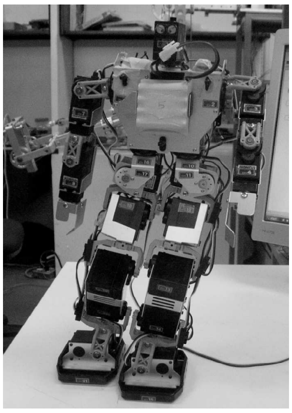

Fig. 4. Center of mass shifts to the left sole, right arm aligned close to the body, left arm front and away from body, right knee slightly bent with right ankle rotating to the right.

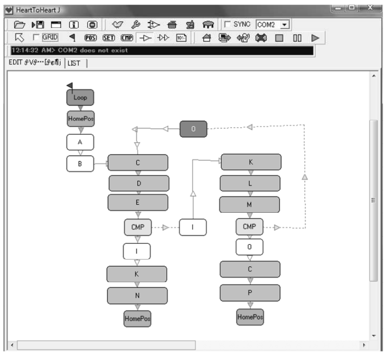

Fig. 5. The 25 positions that compose the Walking forward/backward motion function.

After taking into consideration constraints such as speed, reliability, balance and symmetry, the following is the final configuration for the walking forward motion:

The above positions constitute one step with right leg (C-D) and one step with the left leg (K-M). Depending on the value that is set in the position loop (e.g. x = 5), the position cmploop will decrement x by 1 and compare it with 0 when it is reached. If true, the motion will follow the following sequence: (1) if the last executed position is E, make a partial left leg step by executing positions K and N in preparation for the homeposition, (2) if the last executed position is M, make a partial right leg step by executing positions C and P in preparation for the homeposition. For example if the value in the loop is set to 5, then the following motion will be observed: right step, left step, right step, left step, right step, half left step and then return to home position. In the following we describe the walking backwards and the step right/leftwalking motions. Video clips on the synthesized walking functions for the Kondo humanoid can be found at [10].

The walking backwards 5 has 15 positions. The robot moves backwards by first shifting his center of mass to the left sole of his feet, takes a step backwards with its right leg, shift the center of mass to the right sole, and stay in that position until the robot is stable again, then repeat again but now with a left step. Depending on the value set in the

Fig. 6. Parameterized walking-and-turning function.

counter, the robot will continue to execute this motion until the value is decremented to 0. Finally, the robot prepares itself to return to the home position by taking a half step backwards. A parameterized walking-and-turning function is also designed allowing simultaneous walking with turning by some angle (See Figure 6).

The step right/left has 7 positions. The robot moves backwards by first shifting his center of mass to the left sole of his feet, takes a step backwards with its right leg, shift the center of mass to the right sole, and stay in that position until the robot is stable again, then repeat again but now with a left step. Depending on the value set in the counter, the robot will continue to execute this motion until the value is decremented to 0. Finally, the robot prepares itself to return to the home position by taking a half step backwards. Finally, the turn right/left, swat right/left, kick right/left, bow, and push-ups are implemented in a similar manner.

V. Conclusion

We presented a geometrical model for the walking leg of the Kondo KHR-1 humanoid robot. We also established the mathematical relationships between a set of functional parameters, for walking motion controls, and the leg controlled angles. We also how the model can be used to synthesized a series of points based on the knowledge of the walking pattern in the space of the functional parameters. We used the German team SimRobot simulator to program the soccer scene and for the 3D modeling of the Kondo robot as part of the SimRobot controller. This approach allowed us to analyze the walking motion and provided useful feedback on composition points and motion speed. A set of synthesized walking motions were designed. The result is a library of motions which are: 1) Walking Forward 2) Walking Backwards 3) Step right/left 4) Turn right/left 5) Swat right/left 6) Kick right/left 7) Bow 8) Push-ups. The library will help the students programming the soccer game behavior using the Kondo robot and help them preparing the students to RoboCup competition.

VI. Acknowledgement

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