The 6th Workshop on Humanoid Soccer Robots @ Humanoids Conference, Bled (Slovenia), October 2011.

Robotic Legs - Parameters for a human-like Performance

Jan Carsten Carstensen, Stefan Krupop, Reinhard Gerndt
Ostfalia University of Applied Sciences, Department of Computer Sciences,
Am Exer 2, 38302 Wolfenbüttel, Germany

***Abstract*—When systematically designing technical systems, including robots, a typical first step is to define the requirements. However, when designing humanoid soccer robots, often no clear requirements other than 'behave like a human' are given. With this paper we take a first step towards defining more formal requirements for humanoid soccer robots with non-human-like size. The approach is based on the RoboCup kid-size robot soccer benchmark, specifically the robots ability to kick a ball.**

I. Introduction

The paramount requirement for humanoid robots is a human-like appearance and bipedal locomotion. However, no clear technical requirements are derived from this general claim. Often research is more focused on more intelligent and dynamic motion control [1] [2], but towards the basic parameters of the leg. No implications can be drawn for the design of the robot. So, structural biomimicing humanoids is a typical way of designing a humanoid robot [3]. However, aside from a structural specification, torques and forces at the joints should also be defined.

Humanoid robots have a considerable high complexity and walking is a very complex movement. Therefore, deriving parameters for humanoid robots from walking patterns can be a very cumbersome undertaking [4] [5] [6]. A more easily understandable movement, present in the RoboCup robotic soccer, is the kick of a ball. The kick can be related to a set of actuated coupled pendulums with specific structure, rotational velocities and inertia. The kick-movement is more straight forward and can be modelled more easily. Therefore, for a first formal definition of suitable parameters, we decided to analyse the kick movement and scale human achievements to the robotic scenario. In this paper we start by identifying the human capabilities of kicking a soccer ball and derive from this the general requirements for kicking the ball in the RoboCup kid-size league, i.e. with robots that are 30 - 60 cm high [7]. We then develop the mathematical and physical foundation to derive robot parameters from these requirements. Finally, we present the generic parameters for a humanoid robot with performance parameters for a kick that is comparable to human performance.

II. Requirements

The requirements for robotic soccer need to be related to human soccer. In this section, we discuss how the human achievements can be scaled to the robotic world, specifically the RoboCup kid-size league robots. We consider ratios of the sizes of the fields, of the humanoid and robotic 'players' and the different balls as a means to appropriately scale the requirements for humanoid robot performance.

A first clue for a required performance provides the human soccer field with a typical field size of 105 meters in length and 68 meters in width [8]. From this we derive a necessary kicking distance in a 'real' soccer game between 50 meters (typical) and 100 meters (best case). With respect to the current RoboCup kid-size league field of 6 meters length, this would result in a mean target distance of roughly 3 meters and a maximum kick distance of roughly 6 meters.

A second clue for the required kicking distance can be derived from the size of the robots. For this we assume a human player to have a height of 1.80 m [9] and to immediately control a cylindrical space with a diameter of 80 centimetres. The kid size humanoid robots range in height between 30 and 60 centimetres and typically control a cylindrical space with 30 centimetres diameter [7]. Table I gives a comparison of human soccer players and some humanoid soccer robots of the RoboCup kid-size league. The second and third column show the values used for scaling, the last two columns show the required human-like kick distance scaled by the height and by the diameter for the humanoids.

	Height	⊘	K.dist.(h)	K.dist.(⊘)
Human	1.80 m	0.8 m	50 m	50 m
WF Wolf	0.37 m	0.2 m	10.3 m	12.5 m
FUmanoid	0.6 m	0.3 m	16.7 m	18.8 m
Nao	0.58 m	0.3 m	16.1 m	18.8 m

TABLE I
HEIGHT, DIAMETER AND REQUIRED KICK DISTANCE.

With respect to the maximum size of the kid-size soccer robots, as represented by the FUmanoid robot, the required kicking distance should be in the range of roughly 17 to 19 meters. For smaller robots, like the WF Wolves-Robot, a target distance of 10 to 13 meters would be required in order to reach a performance that scales properly with human performance.

Based on the size of the ball a similar result can be calculated. A soccer ball has a diameter of roughly 22 cm, whilst the kid-size robotic soccer ball, a tennis ball, has a diameter of 6.5 cm. Comparing the diameters of the balls yields a ratio of 0.3 that would correspond with a targeted kicking distance of about 15 meters for the kid-size humanoid robots.

With the presented clues, we conclude that in order to have humanoid soccer robots that scale properly with human soccer players, a mean kicking distance of at least 16 meters has to be reached.

Considering the scaled kicking distances also yields some interesting hints on a suitable field size for the RoboCup kid-size league, which then should be about 32 meters in length for an 11 vs. 11 game. This way, the field length would be twice as long as the typical kicking distance of the robots. Considering indoor soccer, which is played 5 vs. 5 on a field of 40 meters for humans, a respective field for the kid-size robotic soccer should have a length of roughly 20 meters or 1.25 times the mean kicking distance.

III. ROBOTIC BALL KICK

The initial energy of the ball needs to be sufficient to keep the ball rolling over the intended distance. First, we therefore have a short look into the principles of transfering the energy from the robot's leg to the ball.

A. Acceleration of the ball

The process of kicking the ball has the purpose to accelerate the ball in a favourable direction. This is done by using a controlled collision between ball and leg.

1) Underlying physics: We calculate the transfer of energy from leg to ball by means of the principle of colliding objects and the preservation of momentum p (formula 1). We use p for the momentum before and p' after the collision. The momentum of an object is related to its mass and velocity. The mass of the colliding parts of the robot is used in the equation, in most cases this is only the mass of the leg.

$$p_{Leg} + p_{Ball} = p'_{Leg} + p'_{Ball} \quad (1)$$

With masses and velocities put in and the assumption that the ball is resting prior to the kick ($p_{Ball} = 0$), we get equation 2.

$$m_{Leg} * v_{Leg} = m_{Leg} * v'_{CoMLeg} + m_{Ball} * v'_{Ball} \quad (2)$$

However, the collision may not be perfect, i.e. only part of the energy may be transferred between colliding objects. Therefore, every collision can be modelled as a partially elastic and partially inelastic collision where the degree of which a collision is elastic or inelastic is described using the coefficient of restitution c_R [10]. The coefficient of restitution c_R is defined by the quotient of the difference of the velocities of both bodies after the collision v'_{CoMLeg} and v'_{Ball} and the difference between the velocities before the collision v_{CoMLeg} and v_{Ball} as in equation 3.

$$c_R = \left| \frac{v'_{CoMLeg} - v'_{Ball}}{v_{CoMLeg} - v_{Ball}} \right| \quad (3)$$

Using equation 3, formula 4 can be formed to determine the momentum of the ball after the kick.

$$p'_{Ball} = v'_{Ball} * m_{Ball} = \frac{m_{Leg} * v_{Leg} * (1 + c_R)}{1 + \frac{m_{Leg}}{m_{Ball}}} \quad (4)$$

The velocity of the leg, at the point it hits the ball, can be calculated from the rotational velocities of its joints.

2) Approximation: The coefficient of restitution of a tennis ball is approximately 0.79 as being regulated by the ITF rules [11]. To confirm this values we used a simple experiment where we dropped the ball from a defined height H and measured the height of the first bounce, h_1 [12]. The coefficient of restitution c_R can be calculated using equation 6, which can be derived from equation 3 by using equation 5 and under the assumption that the solid floor will have no speed prior of and after the collision. Equation 5 results from the law of conservation of energy and the formulas for kinetic and potential energy.

$$\frac{1}{2} * m * v^2 = m * g * h \quad (5)$$

$$c_R = \sqrt{\frac{h_1}{H}} \quad (6)$$

After a repeated number of tests we were able to confirm the theoretical value of 0.79. With the coefficient of restitution for a tennis ball, the velocity of the ball after the collision can be calculated using equation 7 [13].

$$v'_{Ball} = \frac{m_{Leg} * v_{Leg} * (1 + c_R)}{m_{Ball} + m_{Leg}} \quad (7)$$

The masses of the legs of the humanoid robots in the RoboCup kid-size league, m_{Leg}, typically are in the range of 0.25 kg to 0.5 kg. The ball used for playing has a weight of roughly 0.06 kg. These values would yield a factor between 1.45 and 1.6 for the initial velocity of the ball and the velocity of the leg at the time of hitting the ball. However, experiments showed that the actual initial velocity of the ball is roughly the same as the velocity of the leg during the hit. We used different robots and different legs for testing and in average 0.6 to 0.7 times the calculated velocity values where measured. This discrepancy can be explained by the difference between an ideal one dimensional collision and a real three dimensional one with forces in both horizontal and vertical direction of the kick. We introduce deviation to our further calculations by means of a coefficient of collision c_C by 0.7.

B. Deceleration of the ball

The most significant force to slow down the ball appears to be the roll friction force. As we will show, the initial velocity of the ball after the kick, the mass of the ball and the roll friction are sufficient to approximate the distance the ball will roll.

1) Underlying physics: Our approach to estimate the distance the ball can roll is to calculate the friction work W_F it takes to consume all the kinetic and roll energy of the ball in motion (equation 8).

$$W_F = E_{Kin} + E_{Roll} \quad (8)$$

$$E_{Kin} = \frac{m_{Ball} * v_{Ball}^2}{2} \quad (9)$$

$$E_{Roll} = \frac{\frac{2}{5} * m_{Ball} * r_{Ball}^2 * \omega_{Ball}^2}{2} \quad (10)$$

The kinetic and potential energy are defined by equation 9 and 10 with the radius r and the rotational velocity ω of the ball. The friction work W_F is defined by equation 11

$$W_F = m_{Ball} * g * d * c_{RF} \quad (11)$$

with the gravitational constant g, the distance d and the rolling friction coefficient c_{RF}. From these equations we can derive formula 12 to calculate the distance a ball travels after a kick.

$$d = \frac{0.7 * v_{Ball}^2}{g * c_{RF}} \quad (12)$$

Assuming a constant rolling friction coefficient, the governing variable for the distance the ball will travel is the initial velocity of the ball.

2) Estimation of Roll Friction Coefficient: For a tennis ball rolling on a carpet, no roll friction coefficient can be found in literature. Only for different combinations of other materials, values in the range from almost 0 to 0.4 have been reported. Therefore, experiments had to be conducted to approximate the coefficient for a specific tennis ball - carpet combination.

For this, the tennis ball was placed on a ramp where it was accelerated when rolling down. On the levelled surface the ball then passed through two light barriers to determine its velocity. The distance between the position of the light barriers and the point where the ball settled was measured. The experiment was repeated multiple times. Based on function 12, an average roll friction coefficient of about 0.039 was found.

IV. Implications for the Robotic Leg

Based on the considerations presented in the previous section, a leg needs to hit the ball with a velocity of slightly more than 3 meters per second to achieve a kicking distance of 16 meters. There are many different ways to kick the ball. Currently many teams only use a simple 'stiff' kick model with only the hip-pitch actuator being used for kicking. In a more advanced kick, actuators at the hip, knee and possibly the foot are combined to supply maximum energy to the ball.

A. Simple Kick Model

The simple kick is carried out by only the hip-pitch actuator, moving forward the 'stiff' leg from a backwards position with its maximum velocity. It is assumed that the actuators are sufficiently powerful to accelerate the leg to the maximum rotational velocity of the drive. The velocity of the leg at the point it hits the ball is calculated in equation 13 using the rotational velocity of the servo and the length of the robot's limbs with the distance between the axis of the joint and the point of contact between leg and ball being r and the $rotationalVelocity$ given in rounds per minute (RPM).

$$v_{CoM} = \frac{2\pi * r * c_{CoM} * rotationalVelocity}{60s} \quad (13)$$

Using the principle of the preservation of momentum not the maximum speed, but the speed at the center of mass of the object is used for calculations. In case of the ball being a sphere with even mass distribution, the relevant speed is the average speed. The leg does not have an even mass distribution. In most robotic legs the ratio of the distances between the hip and the the center of mass and the distance between the hip and the foot is roughly 0.7. We consider this ratio as a coefficient of the center of mass c_{CoM}.

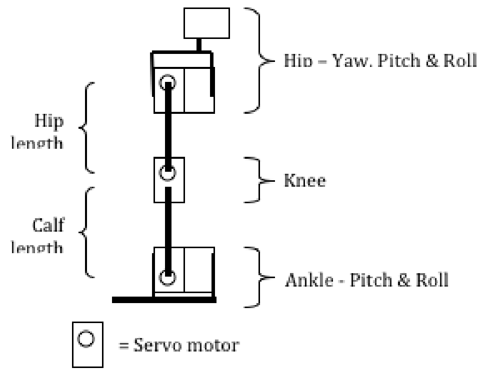

Fig. 1. Schematic of the leg used for the tests.

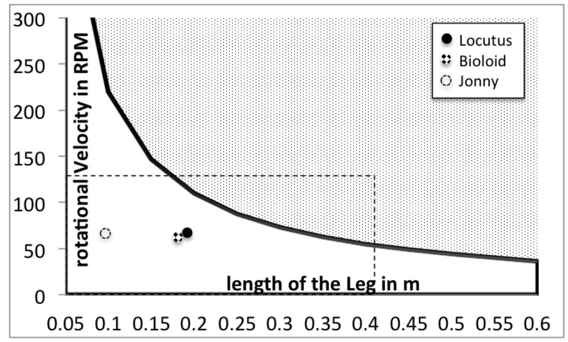

Fig. 2. The required leg lengths and rotational velocities to achieve 16m kick distance for the advanced leg. The black rectangle represents the possible configurations.

B. Advanced Kick Model

A more advanced kick-motion consists of two actuated joints, namely the hip and the knee joint (see figure 1). These two joints contribute to the kick movement. By synchronous actuation of both joints, the rotational velocities add up [14]. Even though this kick is superior to the simple kick with respect to the kicking performance, it also has some disadvantages. For example, timing and stabilizing the robot during and after the kick is more challenging.

The kicking distance d of the simple leg model can be calculated using equation 14, which can be derived from equations 12 , 7 and 13. For the advanced leg the calf and the hip are calculated individualy, here we assumed the proportions of the hip length and calf length being the same. Figure 2 shows the graph for a $16m$ kick for variable rotational velocities ω and length of legs r. Using the equation 14 the graph can be calculated.

$$d = \frac{0.7(c_C * m_{Leg} * 2\pi * r * \omega * c_{CoM}(1 + c_R))^2}{g * c_{RF} * (m_{Ball} + m_{Leg})^2 * 3600s^2} \quad (14)$$

All other parameters in the equation 14 are constant. The horizontal dashed line at $\omega = 126RPM$shows the maximum possible rotational velocity using the currently fastest available digital servo from Robotis, the RX 24F [15]. The vertical dashed line indicates the maximum leg length of $0.42m$ that is in line with the RoboCup Kid Size Rules [7]. Using the RX 24F servo, a minimum leg length of $0.16m$ is required for a kick distance of $16m$. Using the maximum leg length, a minimum rotational velocity of 50 RPM is required for this kick distance. The tests carried out with actual robots (fig. 3) confirm the calculations. The performance of the robots is indicated by dots in the graph.

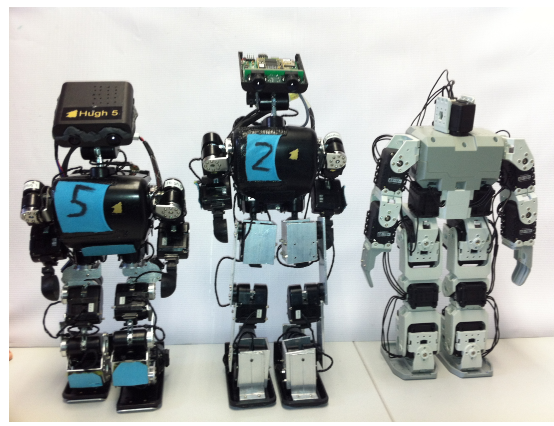

Fig. 3. Robots used for testing. Jonny - WF Wolves 2011 (left), Locutus with modified legs - WF Wolves 2011 (mid) and Bioloid Comprehensive Kit - Robotis.

C. Improving the kick

The important parameters for the kick are the rotational speed of the servo accelerating the leg ω, the length of the leg r and the location of the center of mass c_{CoM}, as well as a coefficient of collision c_C describing how ideal the kick is.

The rotational speed can be improved by using better and faster servos. Another option to increase rotational velocity is to combine two actuators in a single joint, as seen in some robot configurations. Also, the kick distance can be optimized by increasing the length of the leg. The mass distribution can be optimized for kicking by putting more mass into the feet. This will improve kick distances while making other movements harder. Besides this, the mass used for kicking can be increased if the torso is used as extension of the leg and therefore its momentum is added. The coefficient describing the efficiency of the kick can be increased by better aiming, improving the precision of the kick motion and modifying the foot form. For one dimensional surface kicks a plate rising at the tip of the foot can improve results.

V. Conclusion

In this paper we presented a systematic approach to derive the parameters of a soccer-playing robot, based on its ability to kick a ball. Requirements have been referred to human performance, but have been scaled to the size of the robots. Also some clues for the RoboCup kid-size league field size could be derived. For an 11 vs. 11 game a field length of about 32 meters would scale with the human soccer performance and human player size, whilst for 5 vs. 5 a size of 13 to 20 meters would correspond with a human soccer indoor field. A field of 25 to 30 meters would be required if ratios of player and robots and ratios of ball sizes needed to be preserved.

We could show an approach to the estimation of robot requirements, such that the robot performance is comparable to the human performance.

References

[1] H. Mellmann and Y. Xu, "Adaptive motion control with visual feedback for a humanoid robot," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pp. 3169 –3174, oct. 2010.

[2] N. Khemka, C. Jacob, and G. Cole, "Making soccer kicks better: a study in particle swarm optimization and evolution strategies," in *Evolutionary Computation, 2005. The 2005 IEEE Congress on*, vol. 1, pp. 735 –742 Vol.1, sept. 2005.

[3] H. Schempf, C. Kraeuter, and M. Blackwell, "Roboleg: a robotic soccer-ball kicking leg," in *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on*, vol. 2, pp. 1314 –1318 vol.2, may 1995.

[4] N. Patel, S. Pradhan, and K. Shah, "Two legged robot design , simulation and realization," in *Autonomous Robots and Agents, 2009. ICARA 2009. 4th International Conference on*, pp. 426 –429, feb. 2009.

[5] W. K. Chung, Y. Liang, and Y. Xu, "A new transformable mini-humanoid robot: Design and algorithm," in *Robotics and Biomimetics, 2008. ROBIO 2008. IEEE International Conference on*, pp. 590 –595, feb. 2009.

[6] I.-W. Park, J.-Y. Kim, J. Lee, and J.-H. Oh, "Mechanical design of humanoid robot platform khr-3 (kaist humanoid robot 3: Hubo)," in *Humanoid Robots, 2005 5th IEEE-RAS International Conference on*, pp. 321 –326, dec. 2005.

[7] Humanoid League Organizational Committee, "RoboCup Soccer Humanoid League Rules and Setup - for the 2010 Competition in Singapur," 2010.

[8] Fédération Internationale de Football Association, "Laws of the game," 2010/2011.

[9] Statististisches Bundesamt Deutschland, "Körpermaße nach altersgruppen," 2009.

[10] K.-H. H. Grote and J. H. Feldhusen, *Dubbel - Taschenbuch fr den Maschinenbau*. Berlin, Heidelberg, Wien: Springer, 22. neu bearb. u. erw. aufl. ed., 2007.

[11] International Tennis Federation, "Rules of tennis 2011," 2011.

[12] R. Cross, "Measurements of the horizontal coefficient of restitution for a superball and a tennis ball." American Association of Physics Teacher, 2002.

[13] P. McGinnis, *Biomechanics of Sport and Exercise - 2E*. Human Kinetics, 2004.

[14] S. Behnke, M. Schreiber, J. Stuckler, R. Renner, and H. Strasdat, "See, walk, and kick: Humanoid robots start to play soccer," in *Humanoid Robots, 2006 6th IEEE-RAS International Conference on*, pp. 497 –503, dec. 2006.

[15] Robotis, *Dynamixel RX28 Manual*, e-manual v1.08.00 ed.