Roboleg: A robotic soccer-ball kicking leg

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I. ABSTRACT

This paper presents the analysis, design and experimental results of a development program for a robotic leg to be used to kick soccer balls to evaluate new shoe and ball designs for the sport of soccer. The motivation is to be seen in the ability to reproduce and vary kicks reliably to allow more accurate evaluation of new shoe and ball designs without the use of extensive human-kick data sets, statistical evaluations and unquantifiable and unknown experimental errors. The leg was designed with a combination of active and spring-assisted actuator modules to allow the leg to transfer momentum to a soccer ball to achieve take-off speeds of up to 40 m/sec. A removable foot allows for testing of various shoes. Preliminary experimental results have shown that the ball can be kicked with enough range and spin to hit inside the upper corners of a goal at a distance of 20 m and a height of 2.5m with an accuracy of +/- one ball diameter (0.25m), with a maximum range of 40m.

II. INTRODUCTION

Replication of human sports activities using mechanical systems is deemed a useful tool in developing safer and better equipment and fine-tuning athlete's skills. An example similar to the system discussed in this paper, would be the golf-ball hitting robot developed for testing golf-clubs, balls and typical golfer's swings [14]. Our goal was to do the same for the sport of soccer, with the added caveat that the size, weight and impact forces would be at least an order of magnitude larger.

Our project's goal was the design and fabrication of an experimental soccer-ball kicking robot for a large sports-shoe company in order to perform unbiased and repeatable experiments to improve upon shoe and soccer-ball designs. The leg was designed to approximate, as close as possible, the human kinematics and dynamics during the action of kicking a soccer ball. The purpose was to provide a consistent test-bed to remove the statistical variance associated with human testing (current human testing methods involve a professional player taking tens of kicks which are then statistically analyzed) and thus provide objective comparison criteria to judge and drive the design of new soccer-shoe prototypes. In addition, the developed system has the advantage of providing a highly visible, high-tech demonstration and show-piece for the sports-shoe company during trade-shows, press conferences and tournaments.

The system was designed using early-century and the latest photographic and dynamic kicking data available, with the ultimate goal of being able to replicate and alter leg trajectories, configurations, power and contact point and orientation during contact with the ball. We decided to use the joint angle and-velocities as the driving parameters for system performance and power.

III. DESIGN CONCEPT

The overall design concept developed by Bally Design, Inc. and CMU, was originally depicted as shown in Figure 1. It was a basic single-post articulated leg configuration with integrated power, control and display systems.

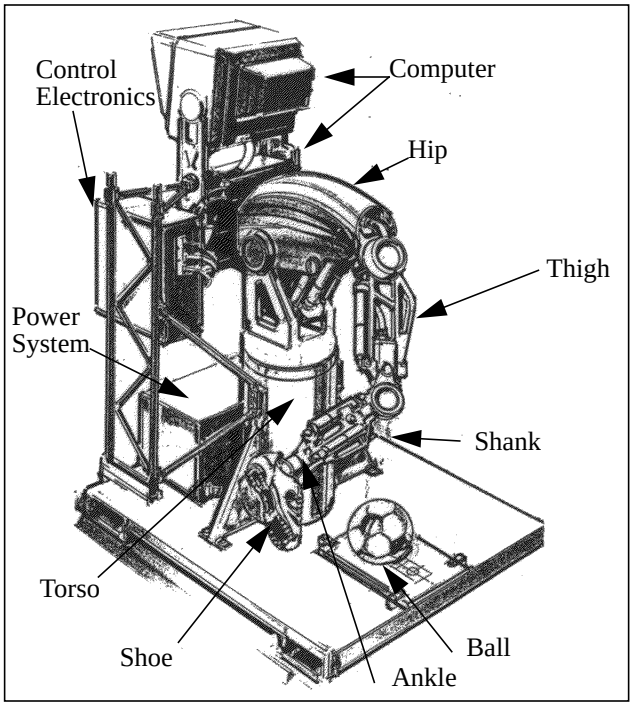

Figure 1: Artist's concept of the robotic soccer leg

IV. BACKGROUND

Much work has been done in the area of biomechanics for the shank [1], foot [2] and ankle [3][4][5], especially as it affects activities such as jogging [6] and other running sports[7][8][9]. Such analyses, modelling and design insights have been useful in applications in single- [10] and multi-legged hopping robots and biped walking robot systems [11].

Very little information exists in terms of data and analyses about the human action of kicking a soccer ball. Some data is purely cinematographic [12], while other data is limited to trajectories, speeds and masses involved in a soccer ball kick [13]. However, the above data could be used to guide the design process of the leg in terms of trajectories, time-frames and impact points and forces. Synthesis of all this data led us then to pursue a passive energy-storage and free-kick release system rather than a completely actively controlled and powered system design.

V. SYSTEM CONFIGURATION

The actual configuration differed only slightly from the concept in that the machine was made to look more 'terminator-like' (meaning no decorative shrouds), and the control computer and display systems were removed from the platform due to concerns of vibration and shock. The final configuration is shown in Figure 2.

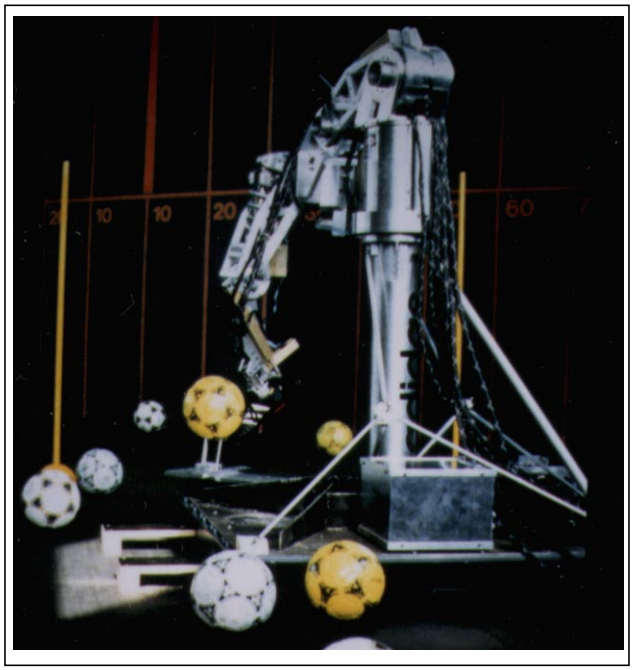

Figure 2: The final *Roboleg* prototype system

The robot consists of a vertical hollow post, supported by tension stantions, mounted on a steel-pallet, upon which are mounted the power and control electronics. The post houses the torso-rotation rotational module, to which are mounted two separate linear actuators to allow for controlling the hip to set leg height and leg-sweep motions. The thigh rotation is actuated using an innovative spring-loaded rotational actuator, to enable the powerful swing of the thigh. A linear spring-loaded actuator is used to power the 'snapping' swing of the shank. Both these actuator modules are innovative in that large power can be transferred to the thigh and shank in a short time period. The ankle is built around a simplified mechanical replica of the achilles tendon by using a small linear actuator to enable toe up/down motions, and a compact rotary and bevel/ring-gearbox to allow for rotation of the toe. A test-shoe is mounted an a foot-lath and attached to the ankle using a simple spanner bolt. This allows the easy testing of different shoes with identical kicking conditions. The ball location is controlled with a translating linear stage which carries a passively pivoting three-prong support to hold the ball until the moment of impact, thus not affecting the impact nor take-off phases of the kick. The entire system is controlled from an IBM-compatible computer and motor controllers which synchronize and coordinate all motions, while a graphical software user interface allows for easy kicking parameter adjustments by the operator.

The kicking sequence is initiated after the ball, hip and foot, and thigh and shank are set in their desired configurations. The individual joints are actuated in sequence (torso->thigh->shank), with their relative release times separated by user-defined delays in milliseconds.

The robot simulates a running kick through the use of the torso rotation and the spring-released thigh and shank 'bones', while the toe is positioned to achieve different contact points and ball-spins. In order to achieve the high ball-speeds upon kicking (~ 40 m/sec), the thigh and shank actuators were designed to be pre-loaded linear and rotary springs which are released via a clutch and then free-wheel to achieve leg-speeds comparable to a professional soccer player in a time-period of less than 0.25 sec., rotationally and linearly accelerating a torso/leg-mass of more than 125 kg and a leg-mass of 70kg to foot-tip speeds of more than 20 m/sec and transferring energy (momentum transfer via elastic collision) to the soccer ball over a contact period of no more than 0.01secs. in length, with impact forces as high as 1,000N. The main difference to a human kick is that the robot is only able to replicate a 1 m/sec running speed using the thigh-rotation, vs. a human with a top speed of around 5 m/sec. Translational speeds at the tip of the foot due to leg rotation are designed to reach between 15 and 25 m/sec.

Active control of the hip (up/down and sweep-angle) and foot orientation are possible, yet due to the short impact times the effect with this machine would be negligible. The follow-through of the leg is similar to that of a human, except that the springs limit the maximum excursions after the ball impact.

VI. KINEMATIC & DYNAMIC ANALYSIS

The kinematics of a typical soccer kick were extracted from work previously published in the literature [12] (see Figure 3). The experimental soccer kick-sequence data led.

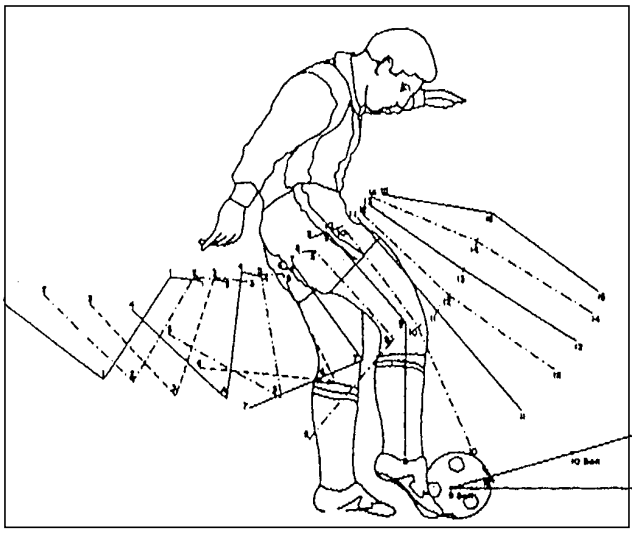

Figure 3: Human kicking sequence

us to develop the kinematic requirements for the leg shown in Figure 4.

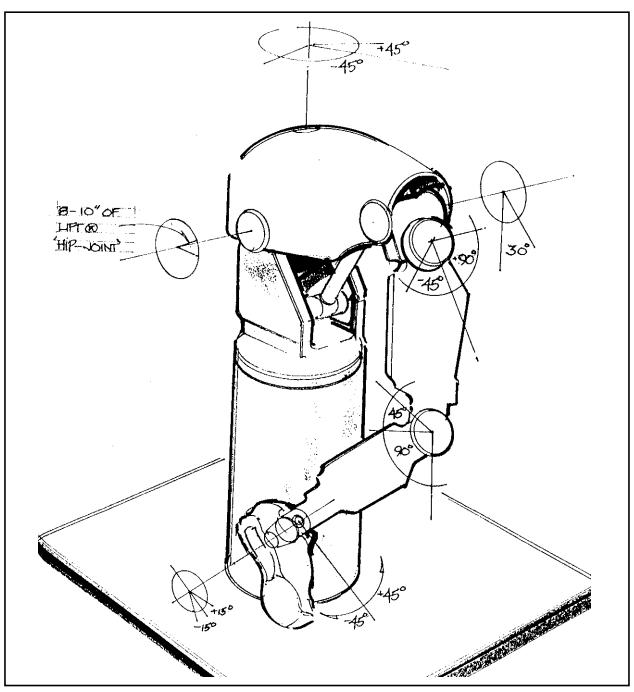

Figure 4: Kinematic configuration for the robotic leg

The torso rotation was set to be +/- 120° w.r.t. the point of impact, while hip-elevation was set to a maximum of 0.2 meters at the thigh-joint and leg sweep was allowed to reach up to 30° from the vertical. The thigh and shank's ranges of motion were set to -45° (flexion) and +90° (extension). The foot allowed ankle rotations of +/-15°, and toe-flexure of +/-45°.

Notice that the ranges of motion for each axis are almost identical to those of the human body, except for the torso rotation, which was extended in order to simulate as fast a running kick as possible through rotational speed.

The dynamic analysis was based on a simplified model of a translating double-pendulum system, with concentrated link-masses and lengths commensurate with that of a human [13]. A dynamic model was developed based on the diagram sown in Figure 5,

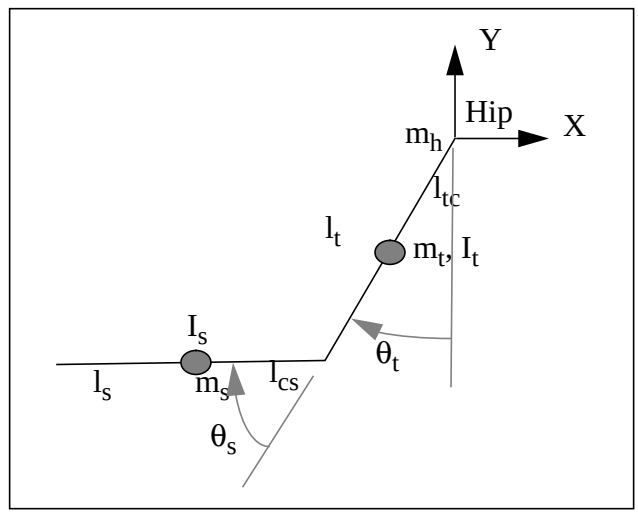

Figure 5: Simplified dynamic *stick-figure* model

with the following constants and variable definitions:

l_t:.....Length of thigh
l_{tc}: .....Length from hip-joint to thigh centroid
m_t:.....Mass of thigh
I_t:.....Thigh inertia about mass-centroid
l_s: .....Length of shank
l_{cs}: .....Length from knee to shank centroid
m_s: .....Mass of shank
I_s: .....Shank inertia about mass-centroid
m_h: .....Mass of hip
θ_t: .....Thigh angle
θ_s: .....Shank angle
x,y:.....Linear hip displacements

The equations of motion used for simulation and dynamic system prediction and analysis were derived using standard Lagrangian methods - a summary of the results and the equations of motion are contained in [15].

Using typical human measures (70 percentile) for weight and lengths for thigh (m_t=35kg, l_t=0.41m) and shank (m_s=23kg,l_s=0.49m), it was determined that the active control and continuous power mode typical for robotic

devices would require a system capable of delivering 13 Hp - a clearly excessive requirement for a compact electric life-size system. This realization led us to further explore the use of controlled energy-storage actuation systems that could be 'energized', and whose stored energy could be controlled during the release phase.

In order to specify actuator performance and design parameters, a simulation was developed that would allow the determination of torso-rotation angle and speeds, thigh and shank spring-forces that would simulate the motions of a human leg and achieve ball-speeds as close as possible to those of professional soccer players. Issues such as wind-up time for the torso, preload angles for thigh and shank, release timing of thigh and shank spring actuators, impact point, follow-through, etc. were all taken into account. The task was one of a multi-parameter search based on quasi-hard constraints on leg trajectories, foot-tip speed, and overall system weight and dimensions. The multi-parameter optimization process (performed using MATLAB) yielded key performance criteria for the actuators, placement and configuration of their mounts on the robot, and the overall discretization levels for sensors, and timing intervals for thigh and shank release during the kick-phase.

A vendor was contracted to design a set of rotary and linear spring-loaded actuator modules for the thigh and shank respectively, based on a set of torque/force and rotational/linear speed specifications developed through the above-mentioned simulation process. A set of linear ball-screw-driven actuators that would preload belleville-washers (thigh) and a coiled spring (shank) were developed capable of developing the large torques and speeds for the thigh (2,000 N-m at 85 RPM) and shank (400 N-m at 165 RPM).

VII. EXPERIMENTAL RESULTS

The leg was tested at Bally Design for proper operation and compliance with the required performance parameters. During the 'burn-in' period we experienced some trouble with premature failure of certain gear-meshes and over-heating of motors, which has since been remediated through material hardening and re-winding of motors.

About 75 kicks were performed before the delivery of the system to ADIDAS, and we determined that the kicked ball could easily hit a wall 20 meters away and at a height of 3 to 5 meters. The impact point was found to be repeatable to within +/- one ball diameter, which we hope to improve upon once the base of the robot is firmly sunk into the floor. Maximum kicking distance was estimated to lie at around 40 meters.

After shipment of the system to ADIDAS in Germany, an additional set of tests was performed in a more realistic setting as shown in Figure 3. The chosen scenario was one of a direct penalty-kick on goal, a distance of about 20 meters away from the goal. A wall of defenders is positioned to protect one side of the goal (10 meters away from the ball), while the goal-keeper is positioned in the opposite corner of the goal. A sure goal would involve swerving the ball around the wall and hitting the goal in the upper corner of the unguarded side of the goal. Hence a shoe with better spin control would give a great advantage to a team. The goal (a wall in this case) is divided into marked divisions in order to establish the actual point of impact.

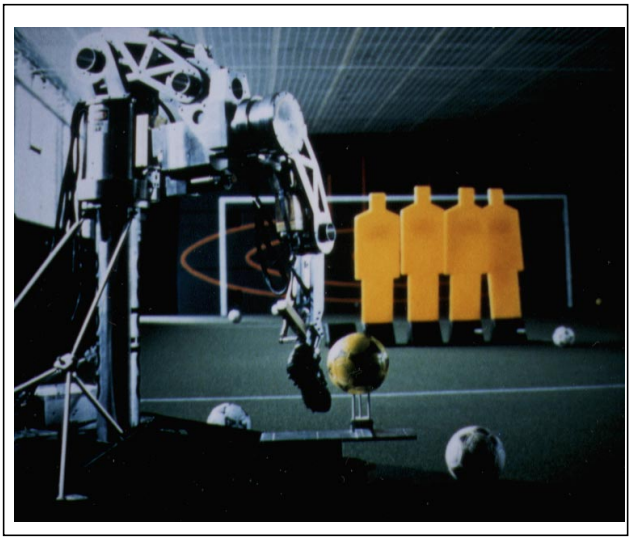

Figure 6: Testing setup for soccer leg in direct goal-kick scenario.

Additional tests will be carried out at Adidas' research facilities in Portland, OR to compare the newly developed shoe, termed the "*Predator*", to the more conventional soccer-shoe models. Test results are deemed confidential until Adidas decides to release them as part of their new product line introduction.

VIII. FUTURE PLANS

The robotic leg will eventually be sited at the Adidas Research Facility in Portland, Oregon. A maintenance contract is being worked out which would allow for continued improvements to the mechanism to increase its reliability and reduce the mean-time-between-failures, and for continued development of operator interface and analysis software. Plans for adding force and torque sensing to the leg joints is being discussed, but it is still unclear whether it would be worth the effort. We hope that all new soccer-shoe models that Adidas develops in the future will have at least been tested using the robotic leg.

IX. ACKNOWLEDGEMENTS

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