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Predicting Soccer Ball Target through Dynamic Simulation

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Authors' contributions

This work was carried out in collaboration among all authors. Author YL performed the dynamics modeling, simulation and analysis, managed the literature searches, wrote the protocol and wrote the first draft of the manuscript. Author JXM established the mathematical equations for the optimization design of a soccer ball motion. Author QL designed the geometric model and performed animation analysis. All authors read and approved the final manuscript.

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ABSTRACT

The intelligent sports analysis of a soccer ball requires accurately simulating its motion and finding the best design parameters (position and orientation) to kick the ball. An optimization method is proposed to plan, evaluate, and optimize the traveling trajectory of a soccer ball. The theoretical studies go through the multi-body dynamics modeling, dynamic simulation, and optimal objective modeling Based on Newton second law and Hooke's law, the motion of a soccer ball is established as the time-dependent ordinary differential equations (ODEs). The expected target is expressed as a function of all design parameters. An example is used to simulate a soccer ball shooting a goal. The result of optimization design has given the most optimal combination of the design parameters, which involve theinitial velocity,initial projectile angle, andinitial orientation angle. This research provides a useful method in predicting the trajectory and adjusting the design parameters for the optimization design of a soccer ball motion.

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Keywords: Soccer ball; multi-body dynamics; initial configuration; dynamic simulation; predicting trajectory; optimization design.

1. INTRODUCTION

Soccer is a worldwide sport that attracts millions of fans. Fans like to see the goal. However, the score of a game is usually low. The 0-0 game is frequently seen, indicating it is not easy to shoot a ball into a goal. This makes fans disappointed. Outstanding soccer players can shoot much more balls on target. Some of them are goals. Therefore, shooting a ball into a goal requires very high skills.

How to shoot a soccer ball into a goal is also attracting scientists and engineers. In simple studies, a simple model used a simplified dynamics model with one free body [1,2]. The equation of motion in the simple models includes only the gravity applied on the ball. This model may apply to the penalty kick and goalkeeper kick. The ball traveling trajectory is similar to the traveling trajectory of a flying bullet.

However, the simple model cannot be applied to the direct free kick. The ball traveling trajectory of a successful direct free kick likes a banana so that the ball flies over the player wall to the goal. A model predicting a banana free-kick must include both the effects of gravity, aerodynamic characteristics (such as the air resistance), and Magnus [3-8]. The effects of the initial velocity, kick force, and kick position on the ball traveling trajectory were investigated [9-12].

The above researches are all based on one free body dynamics. The traveling trajectory can be predicted. They can only apply to free-kick when the ball first hits a target. However, when the ball bounces into the goal, the traveling trajectory cannot be predicted. In our recent study [13], a two-body dynamics model has been created. The contact model between the ball and body has been established. The model can be used to predict the bouncing trajectory.

Further research requires to solve how to shoot a soccer ball into an expected target. This study continues to our previous work and extends the research to develop an optimization method to predict the traveling trajectory. The ball's original trajectory is simulated, and then the optimization operation is applied to find an optimized path. A case study is presented to illustrate the method application.

2. MODELING AND SIMULATION AND OPTIMIZATION

A multi-body dynamics model is created for the simulation of a soccer ball shooting a goal in a virtual field environment. The optimization method is proposed to improve the design parameters and optimize the flight trajectory. The dynamics modeling, virtual simulation, and optimization method are introduced in this Section.

Multi-body Dynamics Modeling: Fig. 2.1 shows a multi-body dynamics model of a soccer ball shooting through the air to a goal in a virtual field environment. For the modeling purpose, a global Cartesian coordinate system o(x,y,z) is attached to the field at the ball center in the initial position. The direction of the x-axis is normal towards the woodwork. The y-axis is perpendicular to the x-axis and normal out of the field. The z-axis is normal to the x-y plane, and its positive direction is out of the x-y plane, which is determined by the right-hand rule.

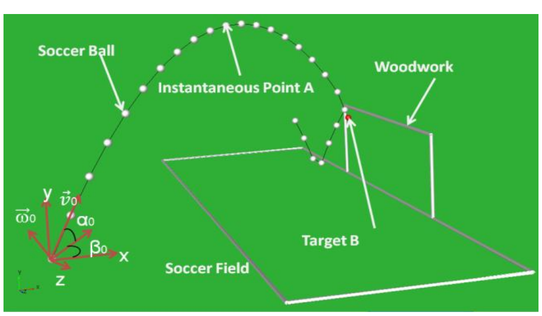


Fig. 2.1. Multi-body dynamics model of a soccer ball-woodwork-field

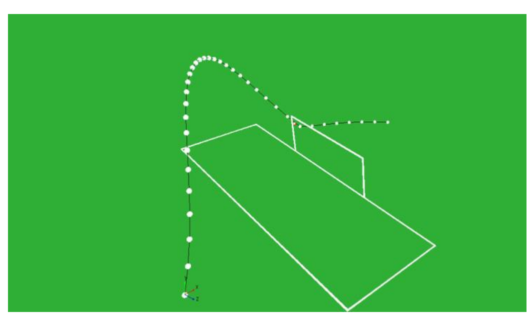


Fig. 2.2. Dynamic simulation of a soccer ball motion with successive ball positions in a virtual field environment.

The model consists of three major components, one ball, one field, and one woodwork. The components are regarded as a multi-body system, related by some restrictions. The field attached to the ground provides a static platform for holding the ball and woodwork. The woodwork is structured by three bars (one crossbar and two goalposts) and mounted on the field by the feet of two goal posts.

Initially, the ball lies on the field with five degrees of freedom (the up-down moving is restricted). The ball is restricted to translate about the y-direction at the center o. However, other five movements are free, which include the translations along with the x and z directions and the rotations around the x, y and z directions. The motion of the ball comprises four distinct phases: (i) the launching at the initial position with an initial velocity and angular velocity in a selected direction, (ii) the spinning around its central axis and the going-up with deceleration and then going-down with acceleration, (iii) the shooting to an expected target, and (iv) the landing on the field.

The motions and forces applied to the ball are established as following Equations.

As shown in Fig. 2.1, the ball is launched at an initial position (x_0,y_0,z_0) with an initial vector $\vec{v}_0$, initial projectile angle θ_0 and initial orientation angle β_0. The initial angular velocity $\vec{\omega}_0$ applied on the ball is normal to $\vec{v}_0$. It can be calculated by $\vec{\omega}_0 = 3s|\vec{v}_0|/r^2$, where s is the vertical distance measured from the center of the ball to the kick force vector; and r is the radius of the ball.

The equation of the ball motion is governed by Newton's Second Law [14].

$$\sum \vec{N} = m\vec{a} \tag{2.1}$$

Where $\sum \vec{N}$ is the vector summation of the general external forces (such as the air resistance, Magnus force, and gyroscopic moment) and the inertia forces (such as gravity and acceleration of Coriolis); m is the mass of the ball; and $\vec{a}$ is the acceleration vector of the ball.

Assuming that the forces applied on the ball include the air resistance, Magnus force, and gravity, Equation 2.1 can be broken into three components in x-y-z directions.

$$m\ddot{x} + K_d\dot{x}^2 - K_m\dot{y}|\dot{y}| - K_m\dot{z}|\dot{z}| = 0 \tag{2.1a}$$

$$m\ddot{y} + K_d\dot{y}|\dot{y}| + K_m\dot{x}^2 - K_m\dot{z}|\dot{z}| + mg = 0 \tag{2.1b}$$

$$m\ddot{z} - K_d\dot{z}^2 + K_m\dot{x}^2 - K_m\dot{y}|\dot{y}| = 0 \tag{2.1c}$$

Where K_d is the air resistance coefficient for considering the effect of the environment on the moving ball, and K_m is the Magnus force coefficient for considering the effect of the environment on the spinning ball.

The equations of motion for ball-woodwork or ball-field contact system are derived by employing Newtown's Second Law and Hooke's law.

$$\sum \vec{N} = m\vec{a} = \vec{F_c} + \vec{F_k} - \vec{W} + \vec{F} \tag{2.2}$$

where $\vec{F_c}$ is the damping force vector, $\vec{F_k}$ is the elastic force vector, $\vec{W}$ is the gravity vector and $\vec{F}$ is the vectors of all other external forces.

Similarly, assuming that the forces applied on the ball include the air resistance, Magnus force and gravity, Equation 2.2 can be separated into three components in x-y-z directions.

$$m\ddot{x} = c\dot{x} + kx - K_d\dot{x}^2 + K_m\dot{y}|\dot{y}| + K_m\dot{z}|\dot{z}| \tag{2.2a}$$

$$m\ddot{y} = c\dot{y} + ky - K_d\dot{y}|\dot{y}| - K_m\dot{x}^2 + K_m\dot{z}|\dot{z}| - mg \tag{2.2b}$$

$$m\ddot{z} = c\dot{z} + kz + K_d\dot{z}^2 - K_m\dot{x}^2 + K_m\dot{y}|\dot{y}| \tag{2.2c}$$

where c is the contact damping coefficient, and k is the contact stiffness.

Motion Simulation: The motion of a ball is simulated subject to all the underlying constraints to visualize and analyze the motions of various positions and the contact information among the ball-woodwork-field. Fig. 2.2 shows the superimposed display of the deployment history of the ball flight in a curve kick in a virtual field environment. The motion is visualized by plotting successive ball positions on graphic displays, which includes curving, bending, and spinning. The numerical results of the motion can be plotted and analyzed to examine the trajectory. The initial parameters can be changed for improving the dynamics performance of the ball flight. The trajectory can be optimized using parametric design, parametric simulation and parametric analysis.

Optimization Design: The optimization design and analysis can efficiently improve the initial parameters design within the required to shoot a target. According to the terminology of optimization modeling, these three factors are redefined their names, such as, (a) the initial parameters design is referred to the design variables, (b) the required range is referred to the design constraints, and (c) the target is referred to the design objective. Three factors play a key role in the optimization process.

If the multi-body dynamics model of a soccer ball has n design variables and each one is denoted by x_i (i=1,2,3,…,n), then all design variables can be expressed by a matrix X

$$X=[x_1, x_2, \ldots, x_n]^I \quad (2.3)$$

Next, the objective function f(X) is associated with these design variables x_i (i=1,2,3,…,n) and can be expressed as a function of the design variables X

$$f(X)=f(x_1, x_2, \ldots, x_n) \quad (2.4)$$

Furthermore, the optimization model is developed and given by Equation 2.5.

$$\min f(X)=\min f(x_1, x_2, \ldots, x_n) \quad (2.5)$$

Assuming m design constraints are requested to apply for the model and each one is denoted by $g_u(X)$ (u=1,2,3,…,m), then the general expression of the design constraints are written as

$$g_u(X)=g_u(x_1, x_2, \ldots, x_n) \geq 0 \quad (u=1,2,\ldots,m) \quad (2.6)$$

It is noted that $g_u(X)$ is related to the design variables x_i (i=1,2,3,…,n). Equations 2.3-2.6 provide an optimization tool to find the design parameters within satisfying design constraints.

Full Procedure Summary: Fig. 2.3 shows a flow chart about the summarized procedure from the multi-body dynamics modeling through dynamic simulation to the design optimization of a soccer ball shooting motion. At the very beginning, a study objective is planned.

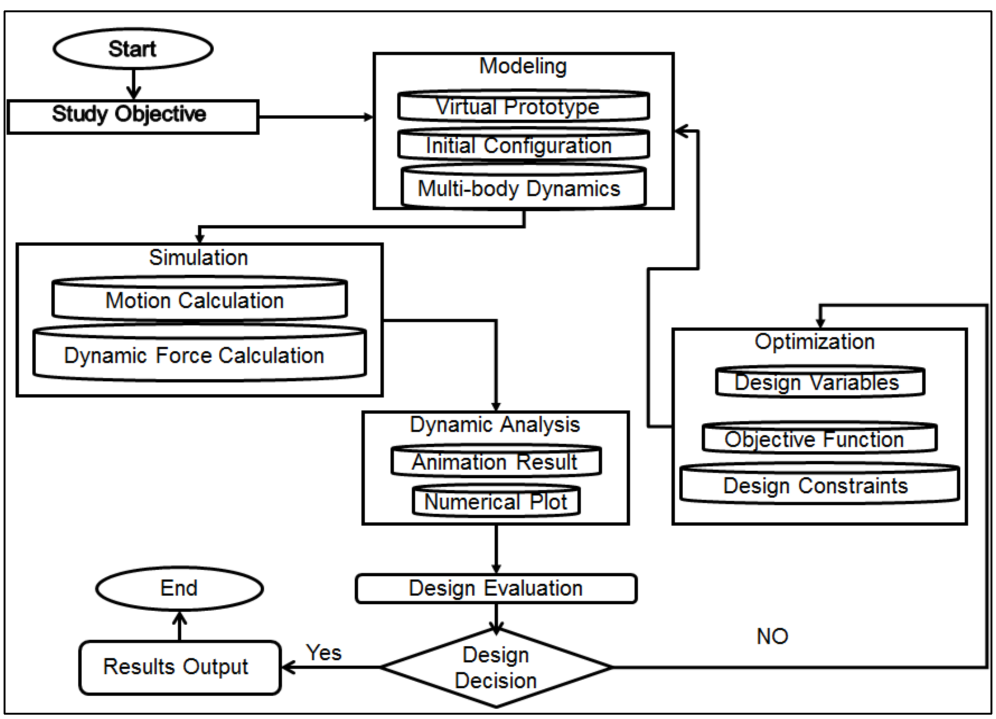


Fig. 2.3. A flow chart for modeling, simulation, and optimization of soccer ball shooting a target

The stage of the modeling involves the virtual prototype modeling of the ball-woodwork-field, initial position and parameter configuration, equations of motion loading on the multi-body dynamics system. Then, the algorithm goes to the simulation stage. The motion parameters and dynamic forces are calculated for each instantaneous position of the ball. The simulation results are output as the animation to visualize the motion and force as well as the numerical diagram to plot all calculated data. These results are analyzed and the dynamic design is evaluated.

The optimization operation adjusts the design variables to minimize the objective function within the constraint ranges. The design variables are set within the constraint ranges. The objective function brings all design variables into a mathematical expression for evaluating purpose. All constraints are defined to keep the optimized design variables within overall limits. The model design can be efficiently improved through the iterative design taking into account to modify the initial parameters to meet the objective requirements. The best values of the design variables are obtained by the optimization operation.

3. ORIGINAL DESIGN AND SIMULATION OF A SOCCER BALL SHOOTING MOTION

In our previous study [13], a case was used for the dynamic simulation and analysis of a soccer ball projectile motion. In this section, continuing the case study, a soccer ball shooting a target is simulated. The works focus on the initial configuration, multi-body dynamics modeling, defining parameters, establishing the motion equations, creating the contact model, and analyzing the simulation results. Table 1 summarizes the general information used in this case study, which includes the geometric parameters, physical properties, and initial conditions. The details are indicated in the following paragraphs.

3.1 Initial Configuration and Dynamic Modeling

The purpose of the case study is to simulate a soccer ball shooting through the air to a selected target. Fig. 3.1 shows a soccer ball's initial configuration, where the soccer ball is located in a virtual soccer field. The virtual prototypes involved in the virtual environment are three solid geometric bodies: (1) a virtual soccer field sized by the length of 120 m and width of 90 m; (2) a virtual soccer woodwork sized by the width WG=7.32 m and height HG=2.44 m; and (3) a virtual soccer ball modeled by the diameter d=0.2286 m and the mass m=0.43 kg [8].

Fig. 3.2 presents a full shooting motion of the soccer ball. A global Cartesian coordinate system o(x, y, z) is attached to the field at the center of the ball. The x-y-z-axis directions are indicated in Section 2. The initial conditions are defined that a soccer ball is initially at rest on the field and is shot with an initial velocity $v_0 = 12\ m/s$at an initial projectile angle θ_0=60°, and an initial orientation angle β_0=30° [13].

The dynamics model of the soccer ball is established under the four assumptions [13]: (1) the air resistance applied on the ball to be homogenous, (2) ignoring the ball flying spin, (3) ignoring the Magnus effect on the ball, (4) ignoring the gyroscopic moment of the ball, and (5) neglecting acceleration of Coriolis. Then, Equations of Motion 3.1-3.3 are yielded for capturing the dynamic behavior of soccer ball in x-y-z directions, respectively.

$$m\ddot{x} + K_d\dot{x}^2 = 0 \quad (3.1)$$

$$m\ddot{y} + K_d\dot{y}|\dot{y}| + mg = 0 \quad (3.2)$$

$$m\ddot{z} - K_d\dot{z}^2 = 0 \quad (3.3)$$

where the air resistance coefficient K_d=0.00622 kg/m [13].

Table 1.The general information: Geometric parameters, physical properties and initial condition

Geometric parameters						Physical properties	Initial parameters		
Field		Woodwork		Ball	Ball	Air	Initial	Initial	Initial
Length	Width	Width	Height	Diameter	Mass	resistance coefficient	velocity	projectile angle	orientation angle
WF (m)	HF (m)	WG (m)	HG(m)	d (m)	M (kg)	K_d (kg/m)	v_0 (m/s)	θ_0 (°)	β_0 (°)
120	90	7.32	2.44	0.2286	0.43	0.00622	12	60	30

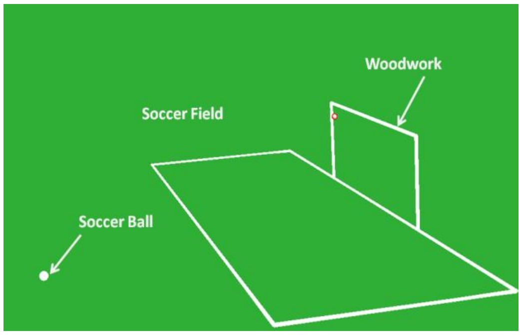


Fig. 3.1. A soccer ball-woodwork-field initial configuration

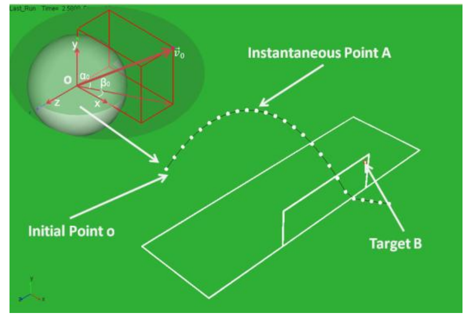


Fig. 3.2. A soccer ball shooting a goal

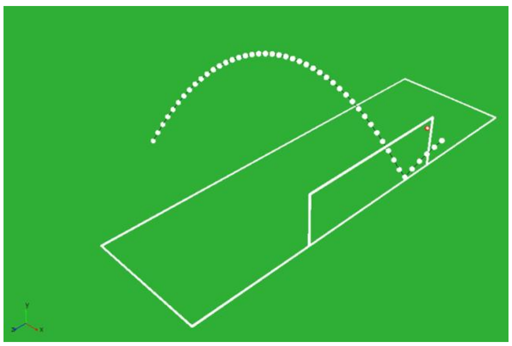


Fig. 3.3. A soccer ball shooting and impacting on the field

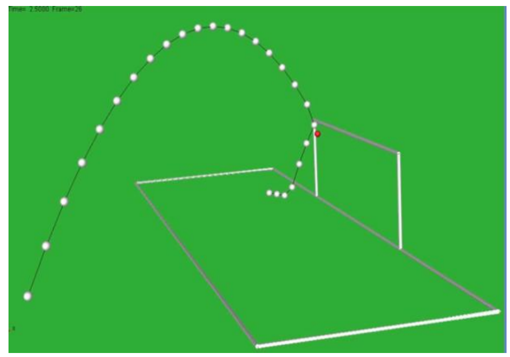


Fig. 3.4. A soccer ball shooting and hitting on the woodwork

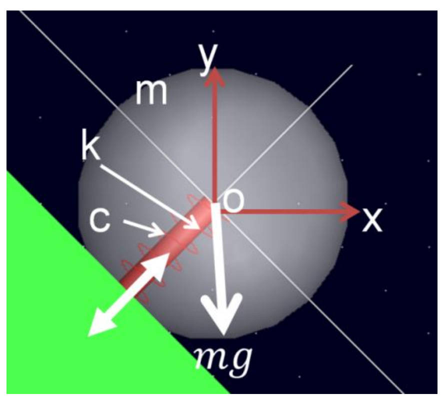


Fig. 3.5. A ball-body contact model with a mass-dumping-stiffness system

In particular, if the ball hits on the field (see Fig. 3.3) or on the woodwork (see Fig. 3.4), the ball-body contact model can be either the ball-field or ball-woodwork. Fig. 3.5 shows a configuration of the ball-body contact with the mass-dumping-stiffness properties. There are three components of motions generated as the ball and body coming into contact in x-y-z directions. The motions then are given as Equations 3.4-3.6, in x-y-z directions, respectively.

$$m\ddot{x} = c\dot{x} + kx - K_d\dot{x}^2 \tag{3.4}$$

$$m\ddot{y} = c\dot{y} + ky - K_d\dot{y}|\dot{y}| - mg \tag{3.5}$$

$$m\ddot{z} = c\dot{z} + kz - K_d\dot{z}^2 \tag{3.6}$$

So far, the initial configuration, parameters design and dynamics modeling are all done. Then, the work turns to simulate and analyze the soccer ball shooting to a target.

3.2 Dynamic Simulation and Results Analysis

The motion simulation is conducted in the virtual soccer ball-woodwork-field environment. Fig. 3.6 shows that the soccer ball shoots from an initial point o(0, 0, 0) through the air to the woodwork at a target B(10, 2.04, -7) with the simulation time t=2.5 s. The animation displays the ball traveling trajectory and reveals the ball position at any instantaneous point A (x, y, z). It notes that the ball traveling trajectory exhibits a parabolic shape and reaches the goal at point B', which almost touches the field. The target B (10, 2.04,-7) is located at the right-top corner. So, the flight trajectory shows the ball doesn't get close to the target B.

To dig out how far away the ball from point B. the numerical results are plotted and investigated. Figs. 3.7a-b plot the ball displacements in x-y and x-z planes, respect-tively. It finds that for x=10 m, then y=0 m (see Fig. 3.7a); and for x=10 m then z=-6 m (see Fig. 3.7b). That means that the ball reaches the goal at point B'(10, 0, -6) and 2.27 maway from target B(10, 2.04, -7). For reaching target B, it is necessary to use an optimization design method to find the best initial parameters, such as the initial velocity, initial projectile angle, and initial orientation angle.

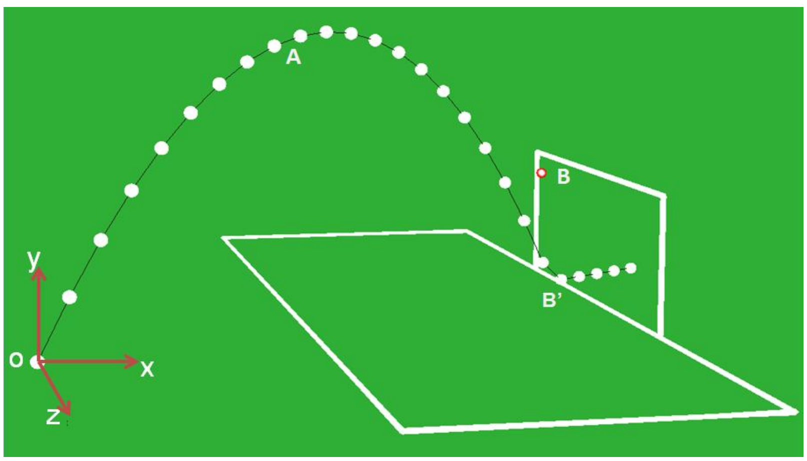


Fig. 3.6 A soccer ball shooting motion verse time 2.5 s with initial velocity v0=12 m/s, initial projectile angle θ0=60o, and aninitial orientation angle β_0=30°

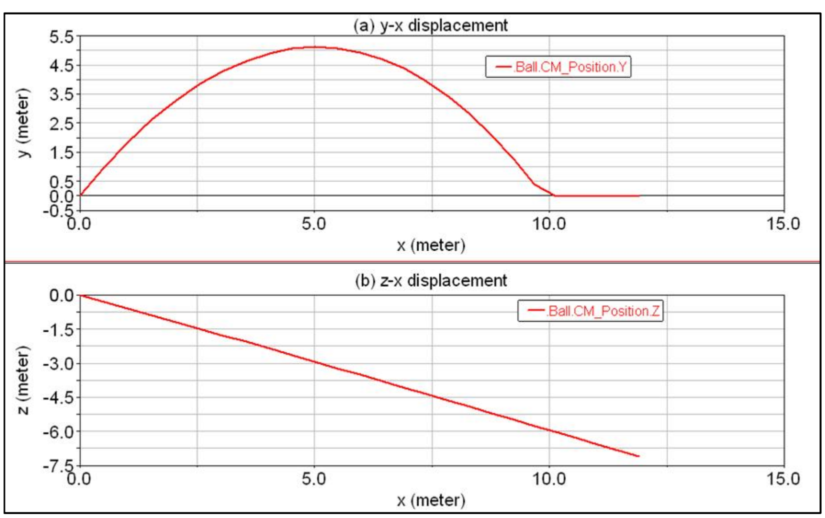


Fig. 3.7. A soccer ball displacements verse time 2.5 s: (a) in x-y plane and (b) in x-z plane

4. DESIGN IMPROVEMENT AND PARAMETERS OPTIMIZATION

The design improvement is performed for the ball to reach the expected target B. The initial parameters are improved to optimize the traveling trajectory. Therefore, the problem becomes to find the best initial velocity v_0, initial projectile angle θ_0, and initial orientation angle β_0 for getting the ball going to a target B. The solution is described in the following steps.

Design Variable Creation: in this case, three independent design variables u_i (i=1,2,3) are involved. The first one is an initial velocity $u_1=v_0$ with a standard value of 12 m/s and the given range between 0 and 30 m/s. The second one is an initial projectile angle $u_2=\theta_0$ with a standard value of 60° and the given range between 0 and 90°. The third one is an initial orientation angle $u_3=\beta_0$ with a standard value of 30°and the given range between 0 and 180°. Three design variables can be installed in a matrix U and expressed as Equation 4.1.

$$U=[v_0,\theta_0,\beta_0]^T=[u_1,u_2,u_3]^T \quad (4.1)$$

Optimization Objective Function: Fig. 3.2 shows thata soccer ball shoots from an initial point o(0, 0, 0) through the air to a target B (x_b, y_b, z_b). The distance L is measured from the instantaneous ball center A (x, y, z) to the target B(x_b, y_b, z_b). The optimization objective is supposed to minimize this distance L and let it smaller than a tolerance. The objective function f(U) is established in a Cartesian coordinate system o(x, y, z) and given as Equation 4.2.

$$f(U) = L = \sqrt{(x_b - x)^2 + (y_b - x)^2 + (z_b - x)^2} \quad (4.2)$$

Design Constraint Definition: the initial ball position on the field cannot be changed. The optimization iterating process will adjust three design variables u_1, u_2, and u_3 within the ranges provided in Section Design Variable Creation. In the optimization program, all constraints are kept larger or equal to zero. Thus, the boundary conditions of the three design variables are defined as

$$g_1(U)=u_1>0 \quad (4.3)$$

$$g_2(U)= 30-u_1\geq 0 \quad (4.4)$$

$$g_3(U)= u_2\geq 0 \quad (4.5)$$

$$g_4(U)= 60-u_2\geq 0 \quad (4.6)$$

$$g_5(U)= u_3\geq 0 \quad (4.7)$$

$$g_6(U)= 180-u_3\geq 0 \quad (4.8)$$

Optimization Process Iteration: The work turns to improve the initial design parameters that meet the objective requirements. The optimization operation automatically finds a better way to approach the minimization of the objective function f(U). The iterative process is performed by varying design variables u_1, u_2, and u_3, which are specified in u_1 within the range [0, 30 m/s], u_2 within the range [0, 90°], and u_3 within the range [0,180°]. For each iteration, the program generates three new values u_1, u_2, and u_3. And then, the program repeats the process for the next iteration. When the difference of the objective values between the current iteration and the last one is less than the tolerance specified 0.04 m, the optimization process is completed.

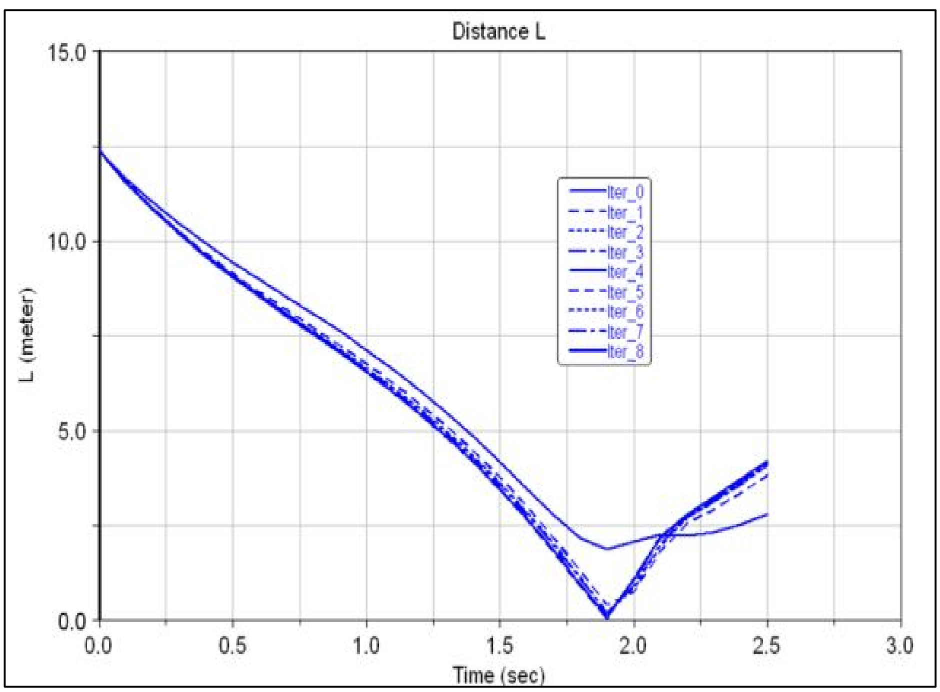
Optimization Iteration Results: in the process of iterating operation, the results of each simulation are examined. Fig. 4.1a captures the variations of measuring distance L verse simulating time t=2.5 s for nine iterations.It can observe the varying tends of nine curves with time. For each curve, distance L decreases from time 0 to 1.9 s, reaches its minimum value at time 1.9 s, and then increases from time 1.9 to 2.5 s. At this minimum distance L, the ball reaches the goal and the traveling time is 1.9 s. If zooming in the area around time 1.9 s, it can find the distribution of minimum distance L verse iteration, as shown in Fig 4.1b. The result shows that it takes nine iterations to get the minimum distance L from the highest value 1.866 m (the first iteration) to the lowest value 0.037 m (the ninth iteration). It also notes that the minimum distance L goes very closely at time 1.9 s and varies from 0.414 to 0.037 m. Anyway, the ball gets closest to point B in the ninth iteration.

Optimization Parameters Determination: Table 2 generates a report about the optimization design results for nine iterations. It lists the minimum objective values and design variables for nine iterations and highlights their initial values and final values. Comparing the original design parameters (standard parameters) with the ninth ones (optimized parameters), the objective value (the minimum distance L) drops 98%, the initial velocity rises 7.03%, the initial projectile angle loses 3.82%, and the initial orientation angle obtains 15.3%. The final results show that the optimization objective value is 0.037 m with the best combination of three design variables, which are the initial velocity $u_1=v_0$ =12.844 m/s, initial projectile angle $u_2=\theta_0$=57.705° and initial orientation angle $u_3=\beta_0$=34.575°.

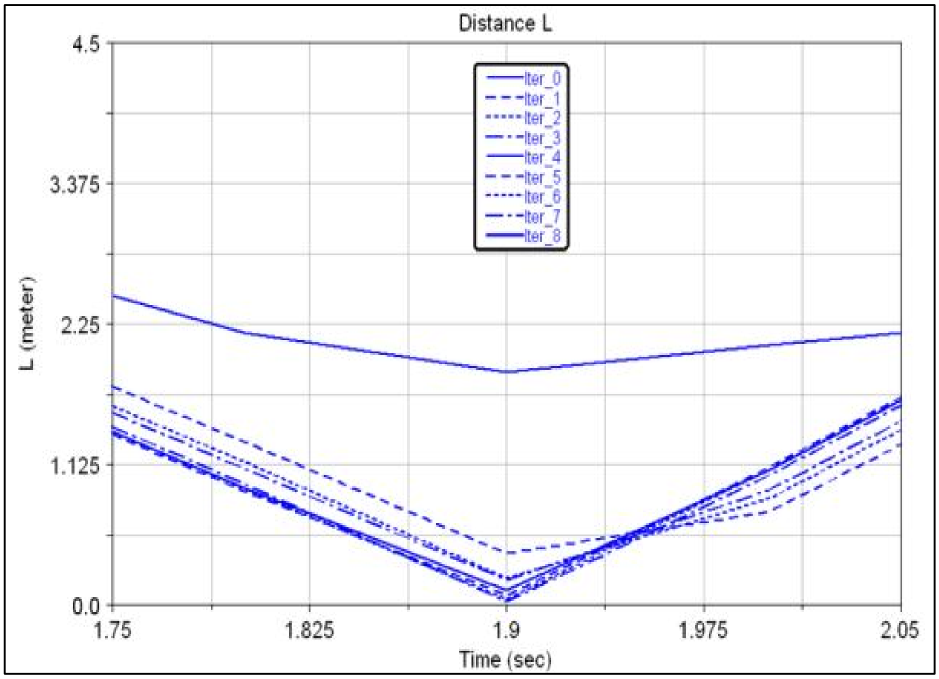
Optimization Results and Analysis: Fig. 4.2 displays the animation result of the soccer ball shooting target B' with the initial velocity v_0=12.844 m/s, initial projectile angle θ_0=57.705°, and initial orientation angle $u_3=\beta_0$=34.575°. It shows that the flight path exhibits a parabolic shape. Comparing the animation result in Fig. 3.6, the actual target B' moves from the right-bottom corner (see Fig. 3.6) to the right-top corner (see Fig. 4.2). The optimized result shows the ball gets close to the expected target B (10, 2.04,-7).

For accurately revealing the position of point B', Figs. 4.3 a-b plot the distributions of the ball displacements in x-y and x-z planes, respectively. Fig. 4.3a shows that for x=10 m, then y=2.05 m. Fig. 4.3b shows that for x=10 m, then z=-7.03 m. Therefore, the ball reaches the goal at point B'(10, 2.05, -7.03) and stays 0.0374 m away from the desired target B (10, 2.04, -7).

Optimization Design Summary: the case study demonstrates the application of the optimization design method to find an optimal trajectory for the ball hitting a target. The optimization operation best meets the performance parameters while satisfying the design constraints. The optimization process involves (i) determining the objective function to minimize the measuring distance L, (ii) selecting the three design variables to be changed, and (iii) specifying constraint ranges to be satisfied. The optimization results are presented in three aspects: (i) the optimized design variables are obtained; (ii) the improved design is simulated; and (iii) the optimized trajectory is visualized. The results show that the combination of the most optimal parameters is the initial velocity v_0=12.844 m/s, initial projectile angle θ_0=57.705° and initial orientation angle β_0=34.575° for achieving the ball to hit the target B within the minimum distance difference of 0.0374 m within the tolerance range 0.04 m.



(a) Simulation time 2.5 s



(b) Zoom-in area around 1.9 s.

Fig. 4.1. Distance-time histories of soccer ball shooting for nine iterations

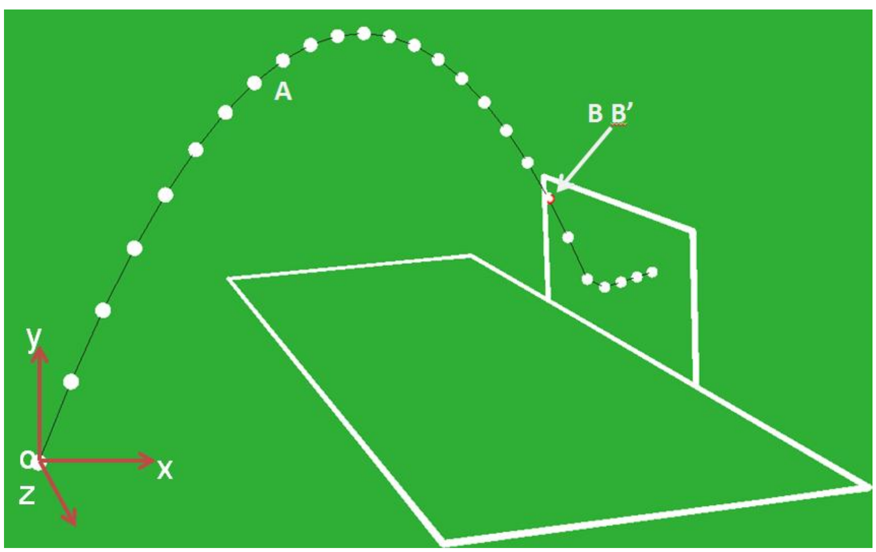


Fig. 4.2. A soccer ball shooting a goal with the initial velocity v_0=12.844 m/s,initial projectile angle θ_0=57.705^o andinitial orientation angle β_0=34.575^o

5. DISCUSSION

The published articles related to this study are introduced in the Introduction. Comparing to their works, the main difference of this study can be specifically described as the following aspects.

Dynamics Modeling: A spatial three-body dynamics model of a soccer ball-woodwork-field is developed, which embeds the air resistance and Magnus force and gravity. In the previous works, the dynamics model was mostly created as a single-body dynamics model and the ball was the only body to taking into account. The researches focused on the studies about aerodynamics characteristics without the contact force item.

In our first phase research [13], a spatial two-body dynamics model of a soccer ball-field has been developed. The model included air resistance and gravity without Magnus force. The equation of the contact force between ~~the~~ ball and field was integrated into the model. In this study, the model is extended to the three-body dynamics model of a soccer ball-woodwork-field, and the Magnus force is added in.

Dynamic Simulation: the parameterization is used for modeling and simulation. This function is required for the full dynamic simulation of the soccer ball shooting. It allows randomly positioning a ball as well as applying a kick force or initial velocity and angular velocity on the ball in 3D space. In recent works [9,10], some simulation systems have been developed to simulate the free-kick of a soccer ball. The trajectory can be predicted for the given initial parameters. However, their works have focused on the kinematics simulation and didn't mention the parameterization problem.

In this study, the motion of the ball can be visualized by plotting successive ball positions on graphic displays. The ball's curving, bending, and spinning postures can be captured in the instantaneous position. There were a lot of studies about flight trajectories. The results have output as the diagrams of the displacement-time, but it may be hard to imagine the position of the ball in the 3D space.

Table 2. The optimization design results for nine iterations

Objectives	**Minimum of measurement distance L (m)**	**Initial value: 1.86566**	**Final value: 0.0373784 (-98%)**	
Design Variables	u1) Initial Velocity (m/s)	Initial Value:12	Final Value: 12.8436 (+7.03%)	
	u2) Initial Projectile Angle (°)	Initial Value:60	Final Value:57.7052 (-3.82%)	
	u3) Initial Orientation Angle (°)	Initial Value:30	Final Value:34.5761 (+15.3%)	
Iterations	**L**	**u1**	**u1**	**u3**
0	1.8657	12.000	60.000	30.000
1	0.41454	12.872	58.558	33.188
2	0.21742	12.943	58.043	34.480
3	0.20106	12.955	57.843	34.324
4	0.11674	12.891	57.491	34.451
5	0.079345	12.844	57.498	34.231
6	0.048698	12.818	57.601	34.327
7	0.028697	12.827	57.710	34.301
8	0.037378	12.844	57.705	34.576

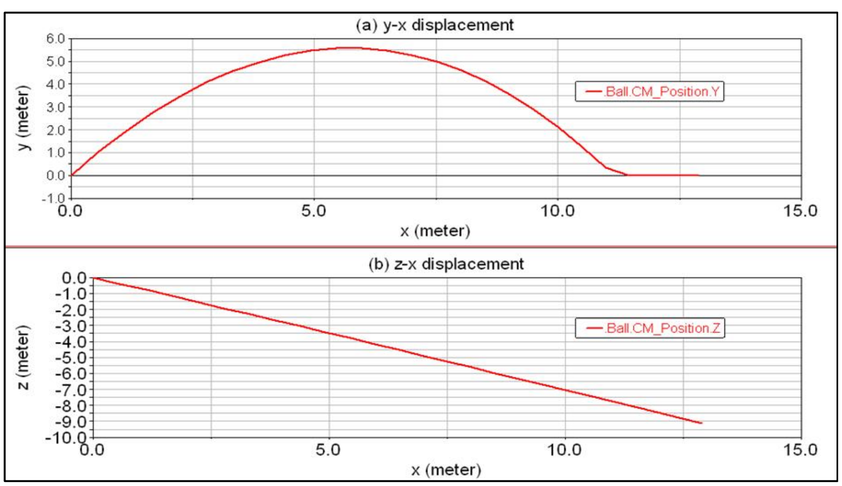


Fig. 4.3. A soccer ball displacements verse time 2.5 s: (a) in x-y plane and (b) in x-z plane

Design Optimization: an optimization method has been proposed to optimize the ball flight trajectory and obtain the best combination of the initial parameters. The design objective has been modeled as the mathematical equations with the design variables and design constraints.The optimization design of ball motion is an interesting subject in sports analysis. The optimization problem usually is about solving an optimal trajectory. Some studies only focused on theoretical model studies. Some studies just armed to improve the original trajectory. Anyway, it is very important to provide a general procedure to describe the flowchart of optimization operation for the advanced sports analysis.

In this study, an example is used to illustrate the method application from the modeling through simulation to optimization design. The most previous studies have focused on the development of a simulation system, but lacked case studies to explain how to use the system.

6. CONCLUSIONS

An optimization method has been proposed to predict a soccer ball shooting a target for promoting the sports analysis. The multi-body dynamics model of the soccer ball-woodwork-field has been established by integrating Newton's section law and Hooke's law with aerodynamics. The motion equations include the items of the air resistance and Magnus force and gravity. A 3D virtual prototype is built to animate the 3D motions of the ball shooting a target. The instantaneous positions of the ball are clearly displayed. To optimize the traveling trajectory, the design objective has been modeled as the mathematical equations with the design variables and design constraints.

An example is given to indicate the application of the optimization design method on the soccer ball shooting a selected target. From the modeling through simulation to optimization, it is concluded that the ball motions can be displayed visually, measured numerically and optimized parametrically. The result shows that the most optimal combination of the design parameters goes to the initial velocity v_0=12.844 m/s,initial projectile angle θ_0=57.705^o andinitial orientation angle β_0=34.575^o for achieving the ball to reach the target. Therefore, the method is useful in monitoring the trajectory and improving the initial parameters.

This study provides a significant approach for the accurate design of the initial configuration to optimize a soccer ball trajectory. Future research will focus on the three aspects: (1) validation of the dynamics model by comparing the experimental results with the simulated results; (2) diversify case-studies by applying the additional factors to the dynamics model, such as Magnus effect, gyroscopic moment, acceleration of Coriolis, and unsteady-state airflow, to illustrate the proposed method further; and (3) ten case studies to apply the method to simulate the successful free and corner kicks in the world-famous soccer games.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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