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Highly Accurate Tennis Ball Throwing Machine with Intelligent Control

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***Abstract*—**The paper presents an advanced control system for tennis ball throwing machines to improve their accuracy according to the ball impact points. A further advantage of the system is the much easier calibration process involving the intelligent solution of the automatic adjustment of the stroking parameters according to the ball elasticity, the self-calibration, the use of the safety margin at very flat strokes and the possibility to placing the machine to any position of the half court. The system applies mathematical methods to determine the exact ball trajectories and special approximating processes to access all points on the aimed half court.

***Keywords*—**Control system, robot programming, robot control, sports equipment, throwing machine.

I. Introduction

ADVANCED tennis ball throwing machines have to accurately launch balls to all locations of the court with all stroke types, strengths and repetition rates in order to realize the game situations. All these should be carried out with high stroke accuracy to perfectly simulate a virtual professional partner for the player. The trajectory of the ball and so the accuracy is determined by the starting parameters of the launch (speed, vertical angle and ball spin), which can be provided either experimentally by videos tracking (as for table tennis [1], [2] or for volleyball [3]) or by its mathematically description. The paper deals with the second method.

Supposing a machine type with rotating wheels for ball ejection, the dynamics of launching cannot described exactly due to the slip-and-stick nature of the ejection [4] containing a purely defined friction [5], [6] the whole process cannot be described exactly. The main influencing factors are the surface roughness of the wheel as well as the elasticity and the remaining nap of the ball [7], [8]. This way, despite the very accurate frequency control and the fine vertical adjustment of the positions [9], the caused spread of the impact points might be disturbing for a high level training.

The aerodynamic behavior of tennis balls are wide ranging investigated [10]-[12] involving the factors that influence the describing Differential Equation System. However, difficulties arise with the mathematical solution of the trajectories when applying them individually for each stroke due to the time required before each launch.

The demand of high accuracy involves the problem of initial validation of the machine as well as the corrections of the strokes during the game. Taking into account the large number of targets the individual calculation of these is impossible. Some former machines evade this problem by limiting the number of the aimed points, dividing the half court into cells, where all points inside are substituted with the center. The stroke parameters of these centers, as the strength and the angles are then computed in advance and stored in a table [13], reducing thus the aiming to a data readout. Additional problems arise when placing the throwing machine into different positions of the court and also because of the spread of the ball elasticity. Therefore, a new development should realize (*i*) the individual *in-situ* measurement of the elasticity of each ball with the determination of their spread for correction of the parameters of each stroke, (*ii*) simplification of the initial validation of the machine as well as the *on-the-game* calibration process and, (*iii*) possibility to place the throwing machine on arbitrary positions.

The paper presents an advanced control system which provides these improvements utilizing mathematical expressions for the trajectories and the measurement of the ball elasticity.

II. Method

A. Impact Points and Trajectories

The main principle of the method is that each stroke should be controlled by its trajectory, namely for all stroke types and training levels and for all aimed points as well as for all positions of the throwing machine.

The impact points are expressed in polar coordinates the origin of which is the actual position of the machine and the axis r ($\varphi=0$) is parallel with the longitudinal axis of the court. The distance of the impact points (s_T) is then given by (1).

$$s_T = \sqrt{(x_T - x_M)^2 + (y_T - y_M)^2}\ ;\ \varphi = arctg\frac{(x_T - x_M)}{(y_T - y_M)} \quad (1)$$

where x_T, x_M, y_T and y_M are the Cartesian coordinates of the impact point and the machine, respectively, and φ is the horizontal angle of the stroke. The distance s_T of the designated impact point and the height of the ball over the net provide the actual trajectory described by the Differential Equation System (2).

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$$\Delta v_x = -(C_D \alpha v^2 \cos\gamma + \eta C_M \frac{1}{2+\lambda} \alpha v^2 \sin\gamma)\Delta t;$$
$$\Delta v_y = -(g + C_D \alpha v^2 \sin\gamma + \eta C_M \frac{1}{2+\lambda} \alpha v^2 \cos\gamma)\Delta t; \qquad (2)$$
$$\Delta x = v_x \Delta t; \qquad \Delta y = v_z \Delta t; \qquad \gamma = \sin\frac{v_x}{v};$$
$$\Delta v = \sqrt{\Delta v_x^2 + \Delta v_y^2}; \quad \lambda = \frac{v}{v_{spin}}; \quad v_{spin} = \frac{d}{2}\omega$$

where v is the speed vector of the ball with the components v_x and v_z , γ is the vertical angle of v, C_D and C_M are the constants of the Drag-force (which retards the motion) and the Magnus-force (which causes a vertical deviation), v_{spin} and ω are the circumferential and angle speed of the ball. Furthermore, $\alpha = \rho\pi d^2/8m$ is calculated from the air density (ρ), the mass (m) and the diameter (d) of the ball, g=9.81m/s^2 is the gravitational acceleration and finally, Δt is the time step.

The trajectories are illustrated on Fig. 1 by a long topspin stroke and a no-spin one, both with the starting ball speed v_0=20 m/s. The height of the throwing point is z_0=0.37m.

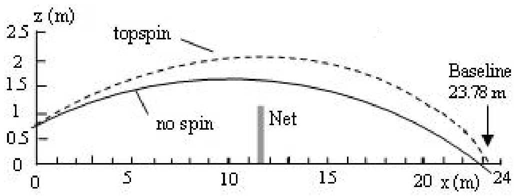

Fig. 1 Illustration of trajectories for two different stroke types

B. Approximations of the Aiming

The numerical solution of the Equation System (2) provides the time function of the speed vector v(t) of the ball from which the x(t) and z(t) coordinates are deduced. The inputs are the stroke parameters (v_0 , γ_0) for the impact point s_T (z=0) and the height of the ball over the net h. However, this is a "reverse calculation" since v_0 and γ_0 are searched whereas the impact point and h are given. This can be achieved only by iteration needing a relatively long computational time thus not available for the *in-situ* application.

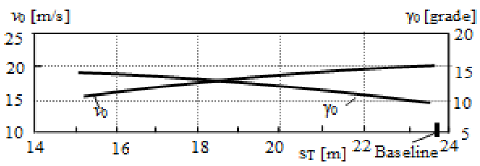

Fig. 2 Starting speeds v_0 and vertical angles γ_0 for different target points along the central line

A possible way to avoid this could be to prepare the $s(v_0, \gamma_0)$ and $h(v_0, \gamma_0)$ functions in advance in an explicit form e.g. polynomials. The derived $v_0(s_T)$ and $\gamma_0(s_T)$ approximating functions provide directly the demanded stroke parameters. Fig. 2 displays the two curves for baseline strokes, minimum ball heights and conventional machine position. However, for general case, due to the large number of variables, this is unsuitable.

The case of high balls is obviously simpler because then the net has no role. Having the starting speed which determines the strength of the stroke, only the vertical angle γ_0 should be calculated. Fig. 3 shows the $\gamma_0(s_T, v_0)$ relations for flat strokes along the central line. The results can also be applied for strokes at different orientations and at different machine positions by a simple shift and/or rotation to the demanded distance s_T.

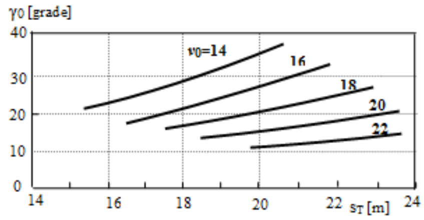

Fig. 3 Vertical angles γ_0 at given speeds v_0 and the distance s_T of target points

The direct approximation method based on the diagrams seems to be appropriate to determine the stroke parameters. However, if the ball is not extremely high then it is necessary to check the height over the net, which means, that, generally, the method is not as simple as it seems to be.

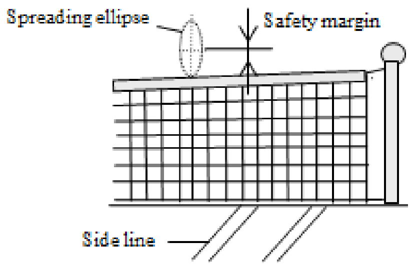

Fig. 4 Illustration of the safety margin applied sideway

In the case of very flat strokes it is necessary to know exactly the spread of the balls in order to choose a reliable ball height over the net. Obviously the spread is smaller just above the net than at the baseline where its vertical size can be determined by guided Monte Carlo analysis using repeated solution of (2). The vertical size delivers a safety margin above which the strokes pass reliably (Fig. 4). This margin is the highest at the side of the court and the lowest at the middle due to the sagging of the net.

C. Dividing the Half Court into Cells

Applying the cell method, the only way to improve the aiming accuracy would be to increase the number of cells resulting in an even larger table for storing the cell data. Another drawback is that because of the large size of the table its correction will be even more difficult.

A more appropriate solution to improve the accuracy is to introduce a local approximation inside the cell. Since the distances inside the cells are relatively small, therefore, using second order polynomial functions the approximation will be acceptable.

Using this method one can exploit that all points inside the cell, being at the same distance from the machine, belong to the same trajectory and so possess the same stroke parameters (neglecting the role of the net). The principle of the approximation is as follows. The designated target will be turned to that radial line which passes through the center and then its distance from the point s_A will be utilized as shown on Fig. 5.

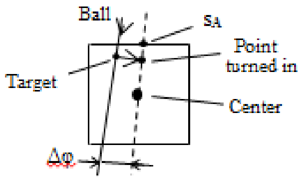

Fig. 5 Illustration of a cell with its center and the displaced target point

The stroke parameters v_0 and γ_0 are computed for the centers by (2) for all stroke types and levels and, in addition, for very flat strokes the height m is also calculated. Accordingly, the data of the centers to be stored consist of the v_0 and γ_0 values for each distance s_T from the machine. However, it should be kept in mind that displacing the machine the allowed height of the ball above the net varies.

The approximation applies a second order polynomial of the stroke parameters to calculate the coefficients. The first order coefficients are the partial derivatives of the function $s_T(v_0, \gamma_0)$ as $a_{1sv} = \partial s/\partial v$ and $a_{1s\gamma} = \partial s/\partial\gamma$, which are the short term quotients of the radial distance and the two stroke parameters. Similarly, the data set contains the linear coefficient of the ball height function above the net $h(v_0, \gamma_0)$ as $a_{1hv} = \partial h/\partial v$ and $a_{1h\gamma} = \partial h/\partial\gamma$. For the second order approximation the coefficients a_{2sv}, $a_{2s\gamma}$, a_{2hv} and $a_{2h\gamma}$ are calculated by (3):

$$a_{2sv} = \frac{ds/dv - a1sv}{2ds}; \quad a_{2sg} = \frac{ds/d\gamma - a1s\gamma}{2ds}; \quad a_{2hv} = \frac{dh/dv - a1hv}{2dh}; \quad a_{2hg} = \frac{dh/d\gamma - a1h\gamma}{2dh} \tag{3}$$

where the parameters ds and dh are the obtained differences for the distance and the height, respectively, furthermore dv and $d\gamma$ are the applied differences inside the cell for the starting speed and vertical angle, respectively, and as a difference for ds the distance of s_A from the center may be applied. Using these coefficients the change of the stroke parameters due to the displacements of the impact point are expressed in (4):

$$\Delta s = a_{1sv}\Delta v + a_{2sv}\Delta v^2 + a_{1h\gamma}\Delta\gamma + a_{2h\gamma}\Delta\gamma^2; \quad \Delta h = a_{1sv}\Delta v + a_{2sv}\Delta v^2 + a_{1h\gamma}\Delta\gamma + a_{2h\gamma}\Delta\gamma^2 \tag{4}$$

where Δh is measured over the crossing point depending on the distance from the sideline.

Although in the second order Equation System (4) the displacements Δs and Δh are given and the differences of the stroke parameters are searched, however, there are fast algorithms to find them. The obtained differences Δv and $\Delta\gamma$ yield the stroke parameters using the expressions $v_T = v_C - \Delta v$ and $\gamma_T = \gamma_C - \Delta\gamma$ where v_C and γ_C are the parameters of the central point.

D. Wheel Frequencies and the Elasticity Measurement

The spread of the ball elasticity significantly influences the stroke accuracy but it can be improved by measuring each ball individually before the ejection. The measured elasticity contains other features as the ablation, the actual nap. However, these factors all influence the ejection and thus they can be involved for the adjustment of the starting speed.

The technical solution of the elasticity measurement is illustrated in Fig. 6. The ball falls down from a ball container into the short pipeline, in which it is pushed forward by the next ball onto the rotating wheels. During the time the next ball is pushed forwards the former waits at the pressure sensor according to the programmed timing.

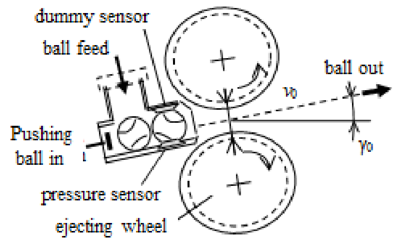

Fig. 6 The ejection mechanism with the pressure measurement

The sensor is placed at the end of the pipeline at the bottom of the pipe with a dummy sensor mounted above. The frequency of the rotating wheels will be adjusted at each ball depending on the measured elasticity. Because the ball is significantly compressed between the wheels so the stroke depends on the elasticity measured. This value will be transferred to the central unit in order to continuously calculate its actual mean and spread.

The speed v_0 should be converted to the frequencies of the wheels. Based on the measurements it was found that the required frequency of the wheels can be approximated by a second order polynomial of v_0. At strokes without spin the frequencies of the upper (f_u) and lower (f_L) wheels are equal, while at spinning balls they significantly differ. The mathematical form of this relation is given in (5):

$$\begin{aligned} &f_u = f_L = (k_1 v_0 + k_2 v_0^2)\cdot k_p; \quad \textit{for flat strokes} \\ &f_u = f_{\max};\ f_L = k_t(rev)\, v_0\, k_p;\ \textit{for topspins} \\ &f_L = f_{\max};\ f_u = k_b(rev)\, v_0\, k_p;\ \textit{for backspins} \end{aligned} \tag{5}$$

where f_{max} is the maximum achievable rotation speed limited by the driving motor, k_1 and k_2 are constants determined experimentally for flat (no-spin) strokes. The k_t constant is used for topspin strokes for the lower wheel and k_b for the upper one for backspins, both depending on the revolution of the spin. In order to achieve the largest revolution the faster wheel always rotates on the maximum frequency f_{max}. All calculated frequencies are multiplied with the elasticity factor k_p provided individually by the measurement. Due to this each ball being either a standard or a private one has its particular k_p coefficient with its mean value and spread, which will be taken into account at the beginning of the game.

E. Playing and Corrections

The flow chart of the play with the interactive stroke corrections is shown in Fig. 7. Starting the game the player enters the main conditions such as the position of the machine, the ball set and the training level to be applied. It is followed by successive entering of the strokes with their type and the impact point. During this the control unit calculates for each stroke (*i*) the φ and s_T polar coordinates of the target point from the x_T, y_T coordinates by searching their incorporating cell, (*ii*) the crossing point over the net, *(iii)* the displacement of the target point from the center, (*iv*) the v_0 and γ_0 values using (5) taking into account the ball height over the net and, (*v*) sends all these data to the machine, optionally completed with the individual waiting time of the stroke.

The machine converts the transferred v_0 values to the wheel frequencies f_U and f_L, according to (5). These frequencies will be adjusted utilizing the measured individual elasticity of the ball while it passes between the sensor and its dummy counterpart. The stroke is carried out after the vertical γ_0 and lateral angles φ are adjusted. The measured values are sent to the central unit.

The system installs some dedicated cells outside of the half court for the correction. If the player detects a faulty stroke then she/he touches the hit cell on the screen of the control unit. So the control unit can identify the fault and modifies either the speed v_0 or the starting angle γ_0 or both. Simultaneously the control unit builds up an error map the evaluation of which may initiate the correction of one part of the table or even the whole map by introducing modified k constants of (5).

III. Results

The presented control system has been tested on an experimental machine based on a former mechanical construction. As control unit a tablet was used with the extended half court represented by its screen and a remote link by WIFI to the throwing machine. The half court has been divided to 96 square cells with 2x2m size from which two test cells are selected at the baseline and behind the net in the center and a third one at the meshing point of the left sideline at the T-line. The *k*-factors of the rotating wheels have been determined for all modes (training level, stroke type and machine position) using (5). (Normally only some of these will be used). Starting experimental shots to these test cells by the player and then touching the observed real impact point on the screen gives feedback for the computing system. Based on these the data of the centers will be corrected and then written into the control unit. Using these data a global table will be built up for the whole half court storing the parameters v_0, γ_0 and φ as well as the approximation coefficients of (3) and (5) for each cells. The machine converts these data to the actual f_u and f_L wheel frequencies.

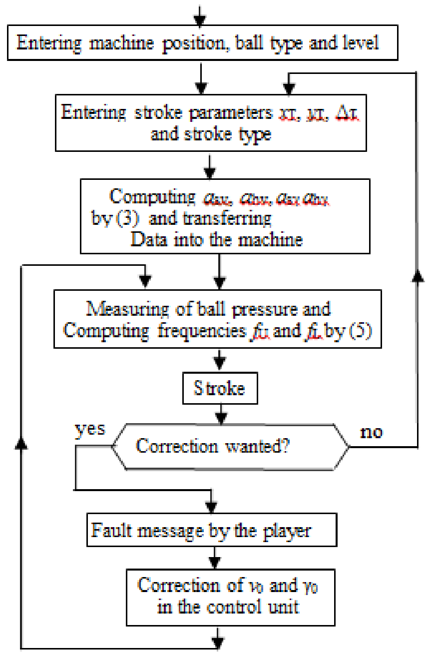

Fig. 7 Flow chart of the play and the interactive stroke correction

The individual elasticity measurements of the balls enable to calculate their up-to-date mean value. When this value significantly drifts away from the former one the control unit rewrites the whole table to improve the accuracy.

The control system has been proven through many thousands of shots using quite different types of balls, too. Using five test shots everywhere on the court less than 65cm deviation of the impact points has been measured. All these justified the excellent stroke accuracy of the developed system and taking the average of the results for a longer time, it can be said to exceed even the launches of some professionals.

IV. Conclusion

The main points of the intelligence of the system are *(i)* introducing an interactive calibration procedure in which the player touches an impact point on the screen and due to this a possible failure is evaluated by the system and then it automatically corrects the stroke parameters even for all stored data of the whole aiming system, *(ii)* the machine is able to do continuous self-calibration on an interactive manner using feedback from the player, *(iii)* allowing the installation of the machine at any position of its half court, automatically adjusting the whole aiming system to this new arrangement, *(iv)* utilizing the spread of balls taking it into consideration when calculating the extremely flat professional strokes. However, allowing using hazardous flat strokes with extremely high strength for professionals, calculating the path of the ball with fault-rates acceptable by the player.

Applying cameras the trajectory of the returns as well as the motion of the player can be observed and evaluated. All these systems inevitably require the use of an intelligent ball throwing machine like the presented one.

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