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To cite this article: Wei Sun et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 493 012019

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Badminton robot batting mechanism design and badminton trajectory simulation

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Abstract. In order to achieve the goal of batting the target quickly and accurately. In this paper, a four-bar linkage mechanism was proposed which used for beating the badminton, and designed a portable badminton robot with omni-directional wheel. Firstly, the 3D model of badminton robot is established. Then the kinematics of batting mechanism is analyzed. Next, the collision of badminton ball is simulated by Adams. Finally, the trajectory simulation for badminton by Particle Swarm Optimization, the parameters of mechanism were optimized.

Keywords: badminton robots; batting mechanism; Particle Swarm Optimization; trajectory simulation.

1. Introduction
Badminton, the racquet sport starts its origins in ancient civilization of Asia and Europe more than 2000 years ago. Moving robot is a hot topic in robot research. At present, all kinds of sports robots such as soccer robot and basketball robot are developing steadily. However, swing arm robots as a branch of this kind of robot develops slowly. The trajectory planning and moving target accuracy of swing arm robot are higher than other robots.

Over the past several years much work has been reported in the literature on swing arm robot. The badminton player movement analyses such as smashing, service, racket swing and shuttle trajectory etc. were mainly carried out qualitatively with substantial human involvement[1]. X. Wang et. al presented two control approaches, Proximate Energy Optimal Servo and Energy-Optimal Model Predictive Control, to improve the energy efficiency of a robot which has to perform point-to-point motions during a fixed time interval[2]. Z. Chen et. al investigated the problem of fast badminton localization problem for a class of badminton robots[3]. S. Mori et. al propose a new robot design that consists of a structure integrated with pneumatic actuators and noninterfering many-degree-of-freedom joints, for the realization of a high-speed and lightweight humanoid robot[4]. J. Stoev et. al present a Mechatronics design approach and related technologies for a badminton playing robot, as a first stage of a multi-year project[5]. P. Janssens et. al consider the problem of energy-optimal time allocation of a series of point-to-point motions[6]. Time optimal control is considered for the hit motion of a badminton robot during a serve operation[7, 8]. The design and research of badminton robot are hot and difficult.
Aiming at the complexity of mechanical arm, this paper designs a mobile badminton robot. The robot uses a three omni-directional wheel chassis as a mobile platform. A four-bar linkage mechanism was proposed which used for beating the badminton. The mechanism is simple, the movement is smooth. To return the badminton at a different angle.

2. Overall structure design of badminton robot
The overall structure assembly model of mobile badminton robot designed in this paper is shown in Figure 1. The mechanical part of the robot is mainly composed of ball loading mechanism, batting mechanism, frame and omni-directional moving chassis.

![Figure 1. badminton robot](image)

1-ball loading mechanism 2-batting mechanism 3-frame 4-omni-directional moving chassis

3. The kinematic analysis of the batting mechanism
The batting mechanism of badminton robot is designed with four-bar mechanism. The pneumatic cylinder is used as the driving force to push the battledore to hit the badminton. The mechanism is analyzed and the schematic diagram is shown in figure 2. Point $A$ is the bracket for the cylinder. Point $B$ is the connection point between the cylinder thimble and the extension rod of the racket. Point $C$ is the fulcrum of the extension rod of the racket. Point $D$ is the center of the battledore. Link $l_{AC}$, $l_{BC}$, and $l_{CD}$ are fixed-length link. The length of the link $l_{AB}$ is the distance between the cylinder bracket end and cylinder thimble head. The change in $l_{AB}$ is the stroke of the cylinder. The tilt angle of the frame is $\theta$. The position angles of link $l_{AB}$, $l_{BC}$, and $l_{CD}$ are respectively $\varphi_1$, $\varphi_2$, and $\varphi_3$. 
The Euler equation is written by the closed loop of the vector. The angular velocity and angular acceleration of each bar can be obtained.

\[
\overrightarrow{AB} = \overrightarrow{AC} + \overrightarrow{CB}
\] (1)

The vector equation above is written as a coordinate equation.

\[
\begin{align*}
l \cdot \cos \phi_1 &= l_1 \cdot \cos \theta + l_2 \cdot \cos \phi_2 \\
l \cdot \sin \phi_1 &= l_1 \cdot \sin \theta + l_2 \cdot \sin \phi_2
\end{align*}
\] (2)

The kinematic analysis is carried out at point D. The coordinates are represented by \(X_D\) and \(Y_D\).

\[
\begin{align*}
X_D &= l_1 \cdot \cos \theta + l_3 \cdot \cos \phi_3 \\
Y_D &= l_1 \cdot \sin \theta + l_3 \cdot \sin \phi_3
\end{align*}
\] (3)

According to the overall size requirement of badminton robot. The parameter of batting mechanism preliminary selected. \(l_1=122\text{mm}, l_2=100\text{mm}, l_3=600\text{mm}\). The stroke of the cylinder is 75mm. \(\theta \in [90, 165]\), \(\theta = 45^\circ\). The movement time of the cylinder is 38ms. The track of the racket was obtained shown in Figure 3.

The batting mechanism of badminton robot is a planar four-bar mechanism, which needs to be converted into space coordinates in practice. In robot design, the chassis coordinates are the world coordinates(WCS). The plane mechanism coordinates are used as user coordinates(UCS). For the convenience of calculation, the four dimensional coordinates are used. World coordinate and user coordinate respectively are expressed as \(\rho'=(x',y',z',1)^T\), \(\rho=(x,y,z,1)^T\).

Coordinate transformation formula:

\[
\begin{pmatrix}
x' \\
y' \\
z' \\
1
\end{pmatrix} =
\begin{pmatrix}
-\sin \alpha \sin \beta & -\cos \beta & -\cos \alpha \sin \beta & X_0 \\
-\cos \alpha & 0 & \sin \alpha & Y_0 \\
\sin \alpha \cos \beta & \sin \beta & \cos \alpha \cos \beta & Z_0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\] (4)
The transition matrix $H$ can be used to convert the plane position of the batting mechanism into space position. Considering the specific spatial layout in robot design, $\alpha = -10^\circ$, $\beta = 45^\circ$. Translation coordinates is (-40,350,645). The corresponding transformation coordinates is obtained.

![Figure 3. the center coordinates of the battledore](image1)

![Figure 4. the space trajectory of the battledore](image2)

4. Dynamic analysis
Due to racquet face is net and badminton is irregular. The model is simplified accordingly. In the absence of friction, energy conservation and momentum conservation:

$$
\begin{align*}
&\frac{1}{2} m_1 u_1^2 + \frac{1}{2} m_2 u_2^2 = \frac{1}{2} m_1 u_1'^2 + \frac{1}{2} m_2 u_2'^2 \\
&m_1 u_1 + m_2 u_2 = m_1 u_1' + m_2 u_2'
\end{align*}
$$

Where, $m_1$ represents the quality of the battledore about 90g. $m_2$ represents the quality of badminton about 5g. $u_1$ represents the speed of the battledore before the collision. $u_2$ represents the speed of the badminton before the collision. $u_1'$ represents the speed of the battledore after the collision. $u_2'$ represents the speed of the badminton after the collision. The speed of badminton and battledore were
calculated by Admas 2013. The speed of badminton was obtained after collision. The power of the batting mechanism is the cylinder. Calculate the cylinder force:

\[ F = \frac{\pi D^2}{4} \rho \eta \]  

(6)

\( D \) is the diameter of the cylinder (20mm). \( p \) is the pressure of the gas source (0.6MPa). \( \eta \) represents efficiency (0.9). According to the actual situation, the parameters of the Admas 2013 model are set. Flexible contact between badminton and battledore face. Then, dynamic simulation is carried out to measure the force and speed of the collision.

From Figure 5, it can be seen the status of badminton collision with the racket. During the collision, the attitude of badminton changes.

**Figure 5.** dynamic simulation of batting badminton

**Figure 6.** the velocity diagram
After the collision, the badminton speed reached about 20m/s shown in Figure 6. The racket speed has been increasing during the collision. During the collision, the speed of the racket decreased by about 2m/s.

![The acceleration change of badminton](image)

**Figure 7.** the acceleration diagram

During the collision, there are two collision contacts, which is the reason badminton's feathers come into contact with the racket. The maximum acceleration of the badminton is about $1.25 \times 10^6$ m/s$^2$.

5. Optimization of badminton track

In order to get a better flight trajectory of badminton, the particle swarm algorithm (PSO) was used to optimize the badminton track. The particle swarm optimization algorithm[9] is a new global optimization evolutionary algorithm developed by Dr Eberhart and Dr Kennedy, which is derived from the simulation of bird feeding behavior.

PSO initializes into a group of random particles (random solution). Then the optimal solution is found through iteration. In each iteration, the particle updates itself by tracking two "extreme values" \((pbest, gbest)\). After finding these two optimal values, the particle updates its speed and position with the following formulas.

\[
V_{i,d}^{n+1} = \omega \times V_{i,d}^{n} + c_1 \times \text{rand}() \times (pbest_{i,d} - x_{i,d}^{n}) + c_2 \times \text{rand}() \times (gbest_{i,d} - x_{i,d}^{n})
\]

\[x_{i,d}^{n+1} = x_{i,d}^{n} + V_{i,d}^{n+1}
\]

Where, \(\omega\) is the inertial weight, \(c_1\) and \(c_2\) are positive constants, called the acceleration coefficient. The change range and velocity range of the \(d\)th particle element are limited to \([X_{d,\min}, X_{d,\max}]\) and \([V_{d,\min}, V_{d,\max}]\) respectively. In an iterative process, if the \(x_{i,d}\) or \(V_{i,d}\) of a one-dimensional particle element exceeds the boundary value, it is equal to the boundary value.

The badminton track has the high ball, the flat ball, the net front ball, etc., the choice of the track is the key which the competition wins. Therefore, the change of trajectory has higher requirements for mechanism. The batting mechanism needs to change the corresponding parameters to optimize the trajectory.

According to Bernoulli equation, air resistance formula:
\[ F = \frac{1}{2} C \rho S v^2 \]  \hfill (9)

Where, \( C \) is the air resistance coefficient. \( \rho \) is air density. \( S \) is the windward area of badminton. \( v \) is for badminton speed.

\[ \sum F_x = \frac{1}{2} C \rho S v^2 \cos \theta ' \]
\[ \sum F_y = -mg - \frac{1}{2} C \rho S v^2 \sin \theta ' \]

The Newton’s second law equation was established. Where, \( \frac{dv}{dt} = a, \frac{ds}{dt} = v \). The relation equation of velocity and time can be obtained by substituting the initial conditions.

\[ v_x = \sqrt{v_0^2 \sin \theta e^{-\frac{2m}{C \rho S \sin \theta}}} \]
\[ v_y = \left( \frac{mg}{(1/2)C \rho S \sin \theta} + v_0^2 \sin ^2 \theta \right) e^{-\frac{2msin \theta}{m}} - \frac{mg}{(1/2)C \rho S \sin \theta} \]

Through analysis, the initial speed of badminton determines the trajectory of badminton. The initial speed of badminton determines the trajectory of badminton. In the batting mechanism, the cylinder pressure \( p \), the tilt angle \( \beta \) of the four bar mechanism, and the angle \( \gamma \) of the racket determine the track of the badminton.

According to the actual situation, the particle swarm optimization model is established. The constraint conditions of trajectory optimization are as shown in formula 12. The three parameters of \( p \), \( \beta \) and \( \gamma \) solved, and the trajectory of badminton is obtained.
Case study, the serve point (-2.0.5) and the landing site (5.4,0) of badminton passing. The mechanism parameters of batting mechanism are obtained \( [p, \beta, \gamma] = [0.58, 42.1, 3.61] \) by particle swarm optimization. The simulation track of badminton is shown in Figure 9.

6. Conclusion
In this paper, a new mobile badminton training robot was proposed. A pneumatic batting mechanism was designed. Kinematics and dynamics analysis are carried out for the model of the mechanism. The structure is simple and the movement is smooth. Simulation of hitting the badminton by Admas 2013 software. In the course of batting, the change of badminton attitude is observed. The particle swarm algorithm is used to simulate the badminton track and determine the mechanism parameters.

Acknowledgments
This work was supported in part by the National Natural Science Foundation of China under Grant (No. 51875418).

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