A Bioinspired 2-DOF Throwing Robot

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***Abstract*—A bio-inspired throwing robot with two degrees of freedom (DOF) was developed for a science center. It has a rotary axis to turn the robot like a human his body and a second rotary axis to throw objects like a human with his arm. With this kinematic, the robot is capable to throw objects into predefined positions within a given 3D-space. The goal of this robot is to demonstrate visitors in the science center robotic throwing with a simple kinematic. In experiments the visitors can learn how the angle of throwing and the speed of throwing determines the trajectories of thrown objects. Student-classes who want to spend more time for the robot can also calculate such trajectories. Therefore, the required mathematical models for this robot are also presented in this paper.**

robot; throwing; trajectory

I. Introduction

For a long time, mechanized throwing or shooting devices are used in sports for training purposes. Already in 1908 a first patent was issued on a “mechanical ball thrower”. This device was able to shoot baseballs with an air-powered gun [1]. Since that time a big variety of throwing devices have been developed. Examples are tennis ball machines, table tennis-machines [2], football-machines [3], golf-swing robots [4], and traps for shooting clay pigeons [5].

During the last years, in more and more research projects, throwing of objects was also investigated in the field of robotics. These researches are based on the advances in dynamic actuators, in fast and high-resolution sensors and in powerful controllers. With that the method of throwing is investigated in particular to demonstrate the features of commercial available robots and robotic components. The first works were also performed, in order to investigate throwing as a new approach for logistic functions in production systems [6, 7].

Based on this trend the experimenta - Science Center der Region Heilbronn-Franken gGmbH in Heilbronn, Germany, together with the Heilbronn University had the idea to present this upcoming method in the field of robotics also for their visitors. The general requirements for a throwing robot were specified as follows:

- The robot should be able to throw a ball accurately into any predefined target point within a 3D-space.
- The kinematic for throwing should have similarities to the movements of humans.
- A simple kinematic of the robot should easily enable the visitors to understand the movements for throwing.
- It should be possible for visitors to learn in experiments the influence of the throwing parameters, which are the angle of throwing (α_0) and the speed of throwing (v_0), on the trajectories of thrown objects.
- For student classes it should be possible to calculate the trajectories.

In this paper the development of a throwing robot for these requirements is presented.

II. State of the Art

In several research works in the past different types of throwing robots with different features were developed and investigated.

A very simple throwing device can be realized when the throwing is performed in a linear motion. Such a motion can be driven e.g. by a spring, a pneumatic cylinder or an electric motor [8, 9]. In order to throw an object into a predefined position within a 3D-space such a device requires, however, at least two additional axes to set the throwing direction.

When objects are thrown by an arm in a rotary motion, only one axis is required to control the speed of throwing and the angle of throwing [10-13]. Since the speed of throwing depends on the length of the arm, with such a configuration also very high throwing speeds can be achieved. Up to now these robots however were investigated mainly in 2D-applications. In [14] an arm with two links (upper arm and forearm) is described. It can be trained to throw and catch objects also in a 2D-plane.

Some commercial available robots also were used for throwing tasks. In the year 1996 an optimized controller for throwing objects by a Scara robot was developed [15]. In [16] a 4-DOF robot (DOF – degree of freedom) is described which is built up with modular components from the Barret Technology Inc. Its end effector can achieve a maximum speed of 6 m/s and an acceleration of max 58 m/s^2. A similar robot is described in [17]. Even humanoid robots are already capable to throw balls. In [18] a video is presented, which shows an impressive throwing experiment of the Sony Qrio robot.

III. 2-DOF Throwing Robot

A. Mechanical Design

The simplest robot kinematic which complies with the requirements in Section I is a 2-DOF robot with two rotary axis as it is shown in Fig. 1. It consists of a first axis (θ_1-axis) which enables a turning of the whole robot in the plane of the ground. This movement corresponds to the turning-motion of the whole body of a human. The second axis (θ_2-axis) corresponds to the arm of a human. It is used for the throwing motion. At first an object like a ball must be loaded into the end effector of the robot. Then, the arm is accelerated to the launching angle. According to the desired throwing parameters (α_0 and v_0), the arm must achieve at this angle a certain speed. When the arm is suddenly decelerated at this point the object will be launched. In this way the two throwing parameters can be controlled with only one axis. The accuracy of such a configuration was already investigated in a previous research work. Tennis balls can be thrown with such an arm over distances of 3 meters with an accuracy of approximately 10 mm [19].

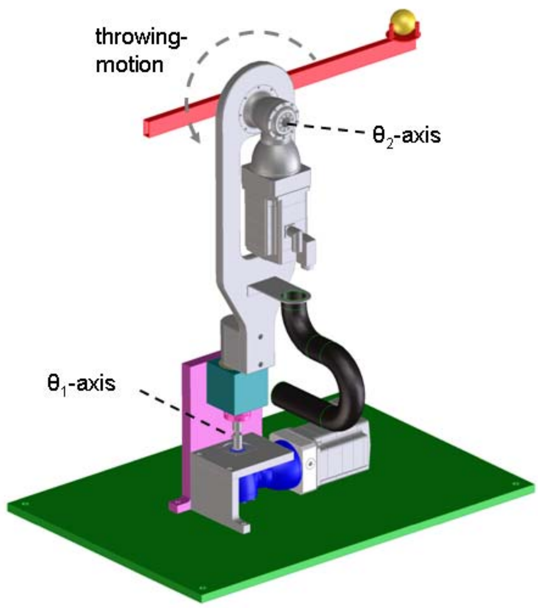
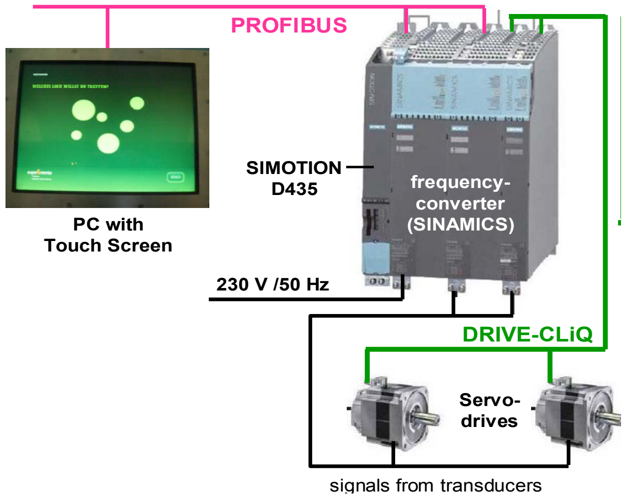


Figure 1. Mechanical design of the throwing robot

B. Control Structure

The control structure of the robot is shown in Fig. 2. A personal computer with a touch screen is used as an operating panel. It is connected over a Profibus to a motion controller, which is a SIMOTION D435 from Siemens AG. It includes already macros for the control of different types of motions. It can be programmed in the SCL-language (SCL - structured control language) which is similar to PASCAL. The controller is connected to a modular frequency converter SINAMICS, which is also from Siemens AG. The drives are servo motors from the same supplier. For the fast acceleration and deceleration of the throwing arm a high dynamic motor with a nominal torque of 4.7 Nm and a maximum speed of 6000 rpm is used. It is coupled to the rotary axis with a gearing (i = 7). Within the drives measuring systems are integrated directly on the motor shafts. With 2048 pulses/rev, a resolution of 0.001° can be achieved.

Figure 2. Control structure



C. Setup

The setup of the robot is shown in Fig. 3. In the exhibition of the science center it is placed in an area which is protected by glass walls. Visitors can handover a ball from outside to the robot via a feeding device. The robot has an arm with a length of 500 mm. With that a maximum speed of throwing of 25 m/s can be achieved. For the operation of the robot in the exhibition

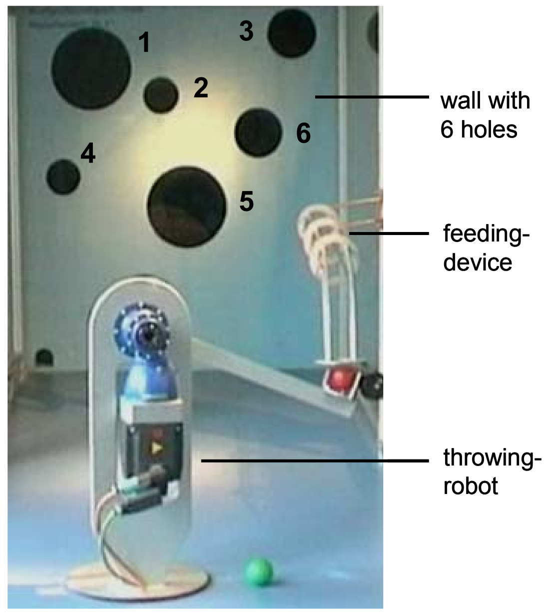


Figure 3. Built up of the throwing robot

this speed however is limited to a range of 8 m/s to 12 m/s. A minimum speed of 8 m/s is required so that the centrifugal force on the ball during an overhead motion of the arm is larger than the force of gravity and so the ball doesn't fall out of the end effector. In a wall six holes with different sizes are prepared as targets for throwing experiments.

The robot can be operated by visitors of the science center via the touch screen in the following steps:

1. A hole in the wall must be preselected as target position T. With this information the robot automatically knows the angle θ_{1T} to turn its θ_1-axis into the direction of T.
2. The operator has to select an angle of throwing α_0.
3. A speed of throwing v_0 must be entered.
4. The throwing cycle can be started by pressing a start-button.

The throwing cycle consists of the following steps (see Fig. 4):

1. After the start-button is pressed, the robot turns from its home position to the feeding device and waits there for a ball.
2. When a person has entered a ball through the feeding device, the robot recognizes this with a sensor. It then turns its θ_1-axis into the direction of the preselected hole (target T).
3. The robot performs with its θ_2-axis the throwing in an overhead motion. Thus for the acceleration an angle of >270° is available, which enables high speeds of throwing.
4. After throwing the robot turns its axes again back into their home positions. From this position the next cycle can be started.

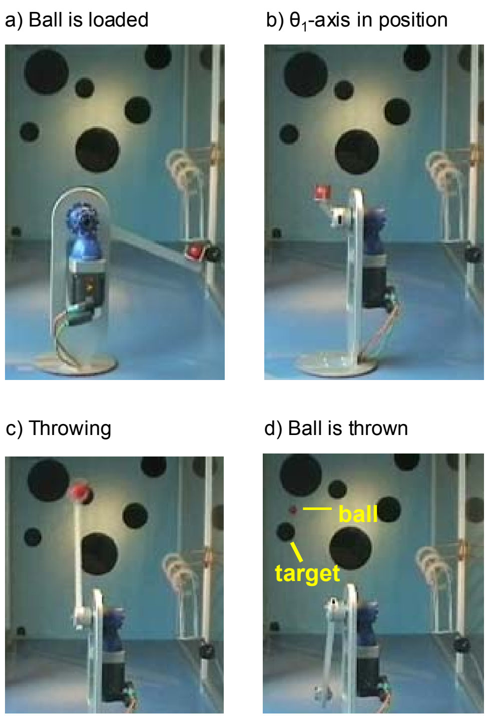


Figure 4. Throwing cycle

D. *Forward kinematics*

The Denavit-Hartenberg technique (D-H notation) is the standard method for describing the forward kinematics of robots [20]. In Fig. 5 three coordinate systems are defined for the throwing robot according to the rules of this D-H technique. From these coordinate systems the D-H parameters can be determined as they are shown in Tab. I. With that a vector ${}^2P$ in the coordinate-system 2 can be transformed into a vector ${}^0P$ in the coordinate system 0 as follows:

$$ {}^0P = {}^0_1T \cdot {}^1_2T \cdot {}^2P = {}^0_2T \cdot {}^2P \qquad (1)$$

The transformation matrices can be determined with the D-H parameters from Table I as

$$ {}^0_1T = \begin{bmatrix} c\theta_1 & 0 & s\theta_1 & 0 \\ s\theta_1 & 0 & -c\theta_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \qquad (2)$$

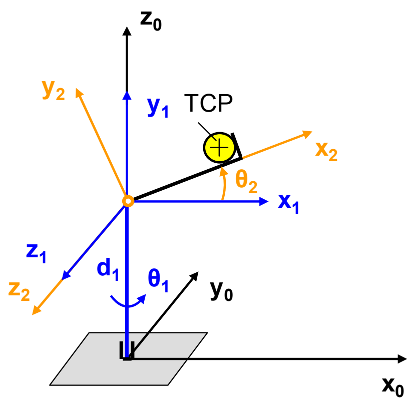


Figure 5. Coordinate system according to the D-H notation

TABLE I. DH-PARAMETERS OF THE 2-DOF THROWING ROBOT

join	a_i	d_i	θ_i	α_i
1	$a_1 = 0$ mm	$d_1 = 100$ mm	θ_1	90°
2	$a_2 = 0$ mm	$d_2 = 0$ mm	θ_2	0°

$$ {}_2^1T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

$$ {}_2^0T = \begin{bmatrix} c\theta_1 \cdot c\theta_2 & -c\theta_1 \cdot s\theta_2 & s\theta_1 & 0 \\ s\theta_1 \cdot s\theta_2 & -s\theta_1 \cdot s\theta_2 & -c\theta_1 & 0 \\ s\theta_2 & c\theta_2 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

IV. CALCULATION OF TRAJECTORIES IN THE 3D-SPACE

A. Mathematical models for trajectories

For an analytical calculation of the trajectories for thrown objects two different mathematical models can be used:

- Model 1:

  If the air resistance is neglected, the position (x, y) of a flying point mass can be calculated over the time with the following well known formulas:

$$ x = v_0 \cdot \cos\alpha_0 \cdot t \quad (5) $$

$$ y = v_0 \cdot \sin\alpha_0 \cdot t - 0{,}5 \cdot g \cdot t^2 \quad (6) $$

  For the calculation of the y-position over x, with equations (5) and (6) the following formula can be achieved:

$$ y(x) = \frac{g}{2 \cdot v_0^2 \cdot \cos^2\alpha_0} \cdot x^2 + \tan\alpha_0 \cdot x \quad (7) $$

- Model 2:

  A mathematical model with the consideration of air drag was developed by P.S. Chudinov [21]. This model has already been approved in several experiments [9]. In this model, at first the coordinates of the apex $A(x_A, y_A)$ and of the end point $E(x_E, 0)$ of a trajectory have to be calculated:

$$ y_A = -\frac{v_0^2 \cdot \sin^2\alpha_0}{2 \cdot g + \frac{k}{m} \cdot v_0^2 \cdot \sin\alpha_0} \quad (8) $$

$$ x_E = -\frac{v_0^2 \cdot \cos\alpha_0}{\sqrt{1 + \frac{k}{m \cdot g} \cdot v_0^2 \cdot \cos^2\alpha_0 \cdot \left(\frac{\sin\alpha_0}{\cos^2\alpha_0} + \ln\tan\left(\frac{\alpha_0}{2} + \frac{\pi}{4}\right)\right)}} \quad (9) $$

$$ x_A = \sqrt{\frac{x_E \cdot y_A}{\tan\alpha_0}} \quad (10) $$

In these equations m is the mass, A is the cross section-area and c_D is the drag factor of the thrown object. Additionally ρ is the air density and k is a factor which can be calculated as

$$ k = c_D \cdot \frac{\rho}{2} \cdot A \quad (11) $$

With the coordinates of the apex A and the end point E the trajectory can be calculated as

$$ y(x) = \frac{y_A \cdot x \cdot (x_E - x)}{x_A^2 + \left(x_E - 2 \cdot \sqrt{\frac{x_E \cdot y_A}{\tan\alpha_0}}\right) \cdot x} \quad (12) $$

B. Application of the mathematical models in the 3D-space

In order to throw an object into a target point T, the robot firstly has to turn its θ_1-axis into the required direction ($\theta_1 = \theta_{1T}$) and then it performs the throw with the θ_2-axis. This leads to a trajectory in the 3D space as it is shown in Fig. 6. For such a trajectory the launching point L can be calculated in the following steps:

- Step 1:

  According to Fig. 7 the position of the launching point ${}^2L(x_{2,L}, y_{2,L}, z_{2,L})$ can be calculated in the coordinate system 2 as

$$ x_{2,L} = l_{arm} - r_{ball} \quad (13) $$

$$ y_{2,L} = r_{ball} \quad (14) $$

$$ z_{2,L} = 0 \quad (15) $$

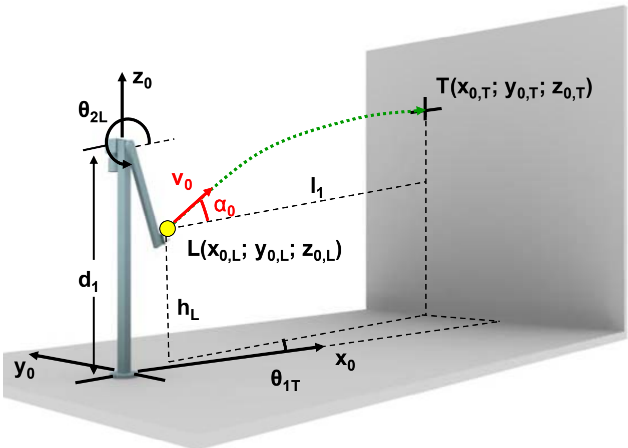


Figure 6. Mechanical design of the throwing robot

- Step 2:

  For the θ_1-axis its angle into the direction of the target can be calculated as (see Fig. 6)

$$\theta_{1T} = \arctan \frac{y_{0,T}}{x_{0,T}} \tag{16}$$

  For the θ_2-axis its angle for the launching point L can be calculated as (see Fig. 7)

$$\theta_{2L} = 270° + \alpha_0 \tag{17}$$

- Step 3:

  With equation (1) the launching point ${}^2L(x_{2,L}, y_{2,L}, z_{2,L})$ can be transformed into the coordinate system 0 ${}^0L(x_{0,L}, y_{0,L}, z_{0,L})$.

For the calculation of the trajectories we now propose to define a new coordinate system 1* as follows (see Fig. 7):

- the origin is in the launching point L and
- the axes are parallel to the axes of the coordinate system 1.

In this new coordinate system the equations (5) to (12) for the models of trajectories can be applied directly. The points of the trajectories then can be transformed into the coordinate system 1 and into the coordinate system 0. Such calculations can be performed and visualized easily with computational software (e.g. Microsoft EXCEL). Fig. 8 shows several trajectories of a tennis ball with different angles of throwing and speeds of throwing.

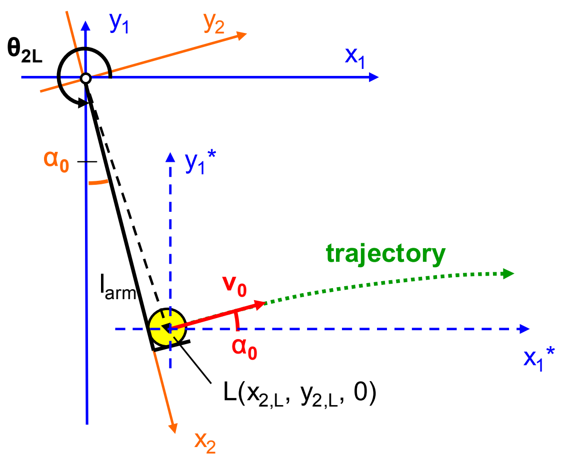


Figure 7. Launching point L in different coordinate systems

C. *Calculation of throwing parameters*

Most visitors of the science center are using the robot in a trial-and-error method. To throw a ball into a preselected hole in the wall they firstly choose an angle of throwing α_0 and then they modify in several retries the speed of throwing v_0.

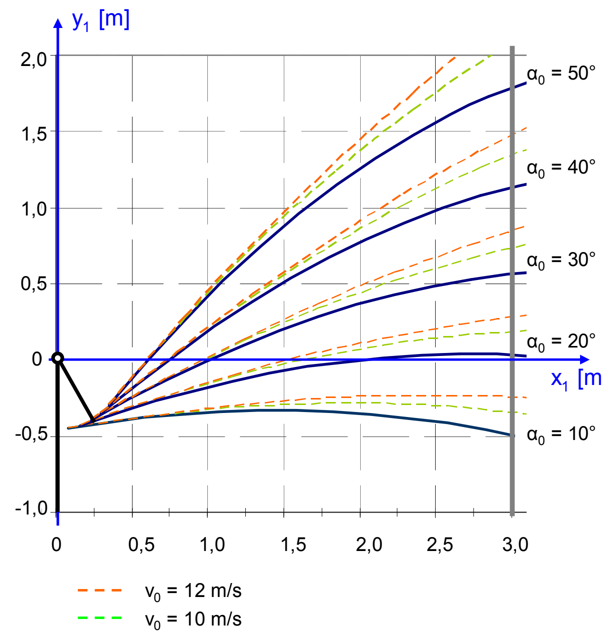


Figure 8. Trajectories of a tennis ball ($m = 56$ g, $A = 32{,}15$ cm^2, $c_D = 0{,}6$ and $\rho = 1{,}293$ kg/m^3)

For student-classes who want to spend more time for the robot, it is also possible to calculate the throwing parameters for a preselected target point T. For that we propose firstly to select a random angle of throwing α_0. This has the advantage, that the launching point L can be calculated immediately with the method described in Section IV, B. In a second step the speed of throwing v_0 must be determined. When using model 1 for the trajectories the following equation can be achieved from equation (7):

$$v_0 = \frac{x^*_{1,T}}{\cos\alpha_0} \cdot \sqrt{\frac{g}{2 \cdot (y^*_{1,T} - \tan\alpha_0 \cdot x^*_{1,T})}} \tag{18}$$

When using model 2 for trajectories, v_0 must be calculated with equations (8) to (12) by an iterative approach. For the calculation of an initial value, equation (18) can be used. The iterative solution then can be performed with numerical methods, such as the Levenberg-Marquard algorithm or the Newton method.

V. CONCLUSIONS

A 2 DOF throwing robot for a science center was presented. It is capable to throw balls (e.g. tennis balls) into any point within a given 3D space. On a touch screen the visitors can select a hole in a wall as a target point. In a trial and error method the throwing parameters then can be varied to meet such a target. With the mathematical models described in this paper it is also possible to calculate these throwing parameters in advance.

The throwing robot in the exhibition of the science center is now longer than half year in use. The statistic evaluation of the experimenta - Science Center der Region Heilbronn-Franken gGmbH shows, that it is one of the most attractive experiments in their exhibition.

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