1-DOF-Robot for Fast and Accurate Throwing of Objects

Heinz Frank, Anton Mittnacht,
Thomas Moschinsky
Reinhold-Würth-University of the Heilbronn
University, Künzelsau, Germany
{frank, mittnacht}@hs-heilbronn.de

Friedrich Kupzog
Institute of Computertechnology, University
of Technology, Vienna, Austria
kupzog@ict.tuwien.ac.at

Abstract

In a research project throwing or shooting is investigated as a new technology for the transportation of objects in production systems. For such an application a 1-DOF-throwing robot with a numerical controlled rotary axis was developed. It can throw objects with masses up to 100 g over distances of more than 10 m. The outstanding feature of the throwing device is, that different angles of throwing and different speeds of throwing can be achieved with only one numerical controlled servo axis. The simple kinematic chain of the robot is also a major reason for achieving a high throwing accuracy. At throwing of tennis balls over a distance of 3 m the accuracy is better than +/- 3 cm. This paper describes the concept, the realization and the test of the throwing robot.

1. Introduction

In a research project we are working on a new approach for the transportation of objects in production systems. Objects shall be thrown from one working station to another by a throwing device and captured by a capturing device [1], [2]. With this approach for the transportation of workpieces, tools, packagings etc. the following basic advantages shall be achieved in future:

- high speeds,
- high flexibilities and
- low costs for resources.

For the realization of this new method basically two classes can be distinguished:

- throwing of objects with indirect hits and
- throwing of objects with direct hits.

When objects are thrown, which are unsymmetrical or not identical, their trajectories are depending on sensitive influences like different conditions during the acceleration by a throwing device or the influence of the gravitation and the aerodynamic resistance during the flight. In this case the objects must be detected on their trajectories by a sensor system and a robot has to move a capturing device during the flight to the final capturing point. Examples for such approaches are described in [3] – [6]. We name this as throwing with indirect hits.

If the objects can be thrown with a direct into a capturing device at a fix position with a direct hit, the sensor system for the detection of the objects on their trajectories and the robot for the movement of the capturing device are not required anymore. Figure 1 shows the basic principle of such an approach. The objects must be accelerated in a certain angle of throwing α_0 and with a certain speed of throwing v_0 to meet the capturing device in the target position T (α_0, v_0 - "launching parameters"). In this paper a 1-DOF robot is presented, which consists of only one rotary axis and which is capable to throw objects with direct hits into predefined target positions.

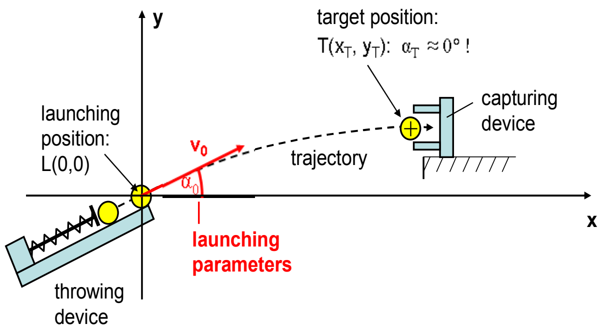


Figure 1. Basic principle for throwing objects with direct hits into a capturing device.

2. Mechanized throwing devices

In production systems devices for throwing or shooting of objects are until today used only for a few specific applications like in weaving machines and packaging machines. Such devices can be found however in the field of sports in many variations. Table 1 gives an overview about existing mechanized throwing devices.

Table 1. Examples for mechanized throwing and shooting devices

application	thrown objects	drive for throwing	speed ; distance
throwing devices in production systems:			
weaving machine [7]	flying shuttle	high speed cylinder	30 m/s ; 30 m
packaging machine	baby diapers	conveyor belts	5 m/s (*) ; 0,3 m (*)
jet cutting [8]	water	water pump	900 m/s; 0,5 m (*)
throwing devices for sports:			
ball machine	tennis ball (m = 65 g)	two wheels	40 m/s ; 40 m
cross bow shooting	arrow (m = 30 g)	bowstring	110 m/s ; 150 m
clay pigeon shooting	clay pigeon (m = 105 g)	spring	20 m/s ; 100 m
gun	projectile (m = 4.1 g)	air pressure (200 bar)	200 m/s ; 500 m

(*) estimated values

For the transportation of objects in production systems by throwing, the following general requirements can be specified for the throwing devices:

- Objects with different shapes, masses and materials shall be thrown.
- The objects must be accelerated in short distances to high speeds.
- To avoid damages, the value for the acceleration shall be adjustable to the features of the objects to be thrown.
- The thrown objects shall meet predefined target positions with a high accuracy.
- Throwing shall be possible with a high frequency.
- The throwing device shall be as simple and cost-effective as possible.

Up to now only few research works can be found for such throwing devices. In [9] a 4-DOF manipulator consisting of alternately revolution and bending motion is presented. With this robot the end-effector can be accelerated with values up to 58 m/s^2 into speeds up to 8 m/s. In a measuring series a urethane ball with a radius of 5 cm was thrown to a target with a radius of 10 cm in a distance of 3 m. The success rate in these throws was about 40 %.

In [10] the simulation of a numerical controlled throwing device with a belt driven actuator is described. The characteristics of the acceleration are good controllable. It can be assumed that with the linear motion a high accuracy can be achieved. The disadvantages of this approach however are that belt driven actuators are available until today only with speeds up to about 10 m/s and that two numerical controlled axis are necessary for setting the two launching parameters α_0 and v_0.

3. Concept for a 1-DOF-throwing robot

3.1. Basic Principle

The basic principle of the 1-DOF-throwing robot presented in this work is shown in Figure 2. An object is loaded into a gripper, which is mounted on an arm. After that the arm is accelerated by a servomotor in a rotational movement during an angle $\Delta\varphi_{acc}$. For the launch of the object, the arm is decelerated by the servomotor. With that the object is released from the gripper and with its kinetic energy the object starts its flight on a trajectory in an angle of throwing α_0 and with a speed of throwing v_0.

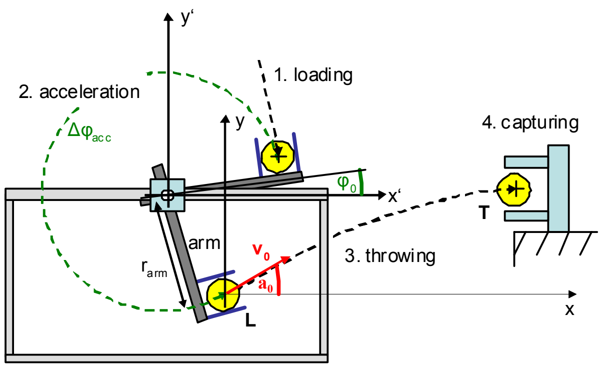


Figure 2. Basic principle of the 1-DOF-throwing robot with a rotary axis

This concept has in particular the following outstanding features:

- With the control of only one servo motor at the launching point different angles of throwing and different speeds of throwing can be generated. With this it is not only possible to meet different target positions but also to achieve different angles of the trajectory in the target point [11].
- Since the speed of throwing v_0 is proportional to the length of the arm (r_{arm}), for v_0 very high values can be achieved.
- The simple kinematic chain consists only of a minimum of components which can cause errors. So a high accuracy can be achieved with this approach.
- The realization of this concept is very cost-effective.

3.2. Specification of the launching parameters

The trajectories of thrown objects can be calculated with Newton's law and under consideration of the air-drag force proportional to the square of the velocity [12]. Therewith the following differential equation can be achieved:

$$\dot{\vec{v}} = \vec{g} - g \cdot k \cdot |\vec{v}| \cdot \vec{v} \quad (1)$$

In this equation v is the speed, g is the acceleration due to gravity and k is a proportionality factor with

$$k = \frac{\rho_a \cdot c_d \cdot A}{2 \cdot m \cdot g} \quad (2)$$

In equation (2) ρ_a is the air density, c_d is the drag factor of the thrown object and A is the cross-section area of the thrown object. The detailed equations for the calculation of the trajectories are described in [11].

At the beginning, tennis balls shall be thrown with the throwing device as example objects. For such tennis balls the parameters for equation (2) can be assumed as ρ_a = 1.293 kg/m^3, c_d = 0.6, A = (32 mm)$^2 \cdot \pi$, m = 56 g and g = 9.81 m/s^2 [13]. Therewith the trajectories can be calculated for different launching parameters v_0 and α_0. With the trajectories shown in Figure 3 it can be concluded that the launching parameters $v_0 \leq 15$ m/s and $\alpha_0 \leq 90°$ will allow to meet predefined targets in a range of $0 \text{ m} \leq x \leq 8 \text{ m}$ and $0 \text{ m} \leq y \leq 8 \text{ m}$.

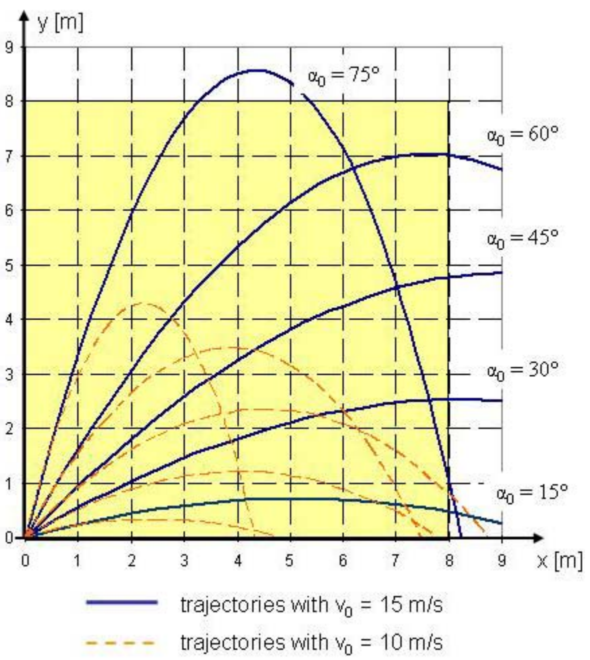


Figure 3. Trajectories of a tennis ball at different launching parameters v_0 and α_0

3.3. Required accuracy

For throwing the tennis balls into a capturing device at a fix position the throwing device must be accurate enough. The influence of an error in the speed of throwing e_v and in the angle of throwing e_α can be calculated as it is described in the following.

At first the exact trajectory is assumed as

$$y = f(x, v_0, \alpha_0) \quad (3)$$

With an error e_v in the speed of throwing the trajectory can be calculated as

$$y = f(x, v_0 + e_v, \alpha_0) \quad (4)$$

So the error caused by e_v on the trajectory can be calculated as

$$e_y = f(x, v_0 + e_v, \alpha_0) - f(x, v_0, \alpha_0) \quad (5)$$

The characteristics of this error e_y is shown in Figure 4 for different speeds v_0 each with an error $e_v = 0{,}01 \cdot v_0$.

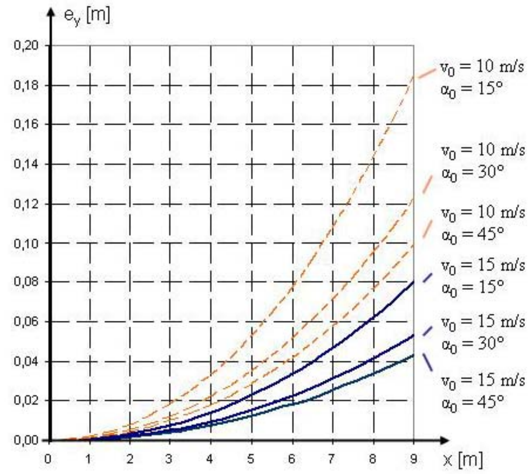


Figure 4. Error in the y-position of a trajectory (e_y) caused by an error $e_v = 0.01 \cdot v_0$

With an error e_α in the angle of throwing the trajectory can be calculated as

$$y = f(x, v_0, \alpha_0 + e_\alpha) \quad (6)$$

So the error caused by e_α on the trajectory can be calculated as

$$e_y = f(x, v_0, \alpha_0 + e_\alpha) - f(x, v_0, \alpha_0) \quad (7)$$

The characteristics of this error is shown in Figure 5 for different angles α_0 each with an error $e_\alpha = 1°$.

With these considerations it was specified that the prototype for the throwing device shall support speeds of throwing v_0 with an accuracy of better than 1% and angles of throwing α_0 with an accuracy of better than 1°.

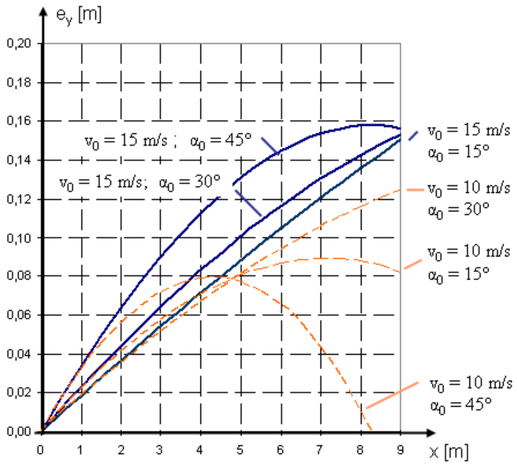


Figure 5. Error in the y-position of a trajectory (e_y) caused by an error e_α = 1°

4. Realization

The mechanical construction of the 1-DOF-throwing robot with a rotary axis is shown in Figure 6. The mechanics of the rotary axis consists of a gearing (i = 7), a clutch, a shaft and an arm. The arm has a length of r_{arm} = 460 mm. This mechanics is driven by a servo motor Siemens 1 FK 7 with a nominal torque of 4,7 Nm and a maximum speed of 6000 rpm. Within the drive a measuring system is mounted directly on the motor shaft. With 2048 pulses/rev finally a resolution of 0.001° can be achieved.

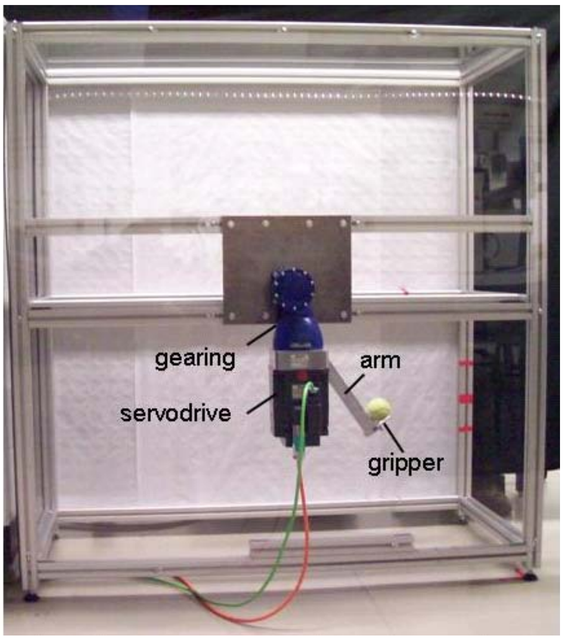


Figure 6. Mechanical construction of the 1-DOF throwing robot

For the control of the rotary axis a motion control Siemens SIMOTION D435 and a frequency converter Siemens SINAMICS is used (Figure 7 and Figure 8). This system includes on a microcontroller the standard functions of modern motion controllers. It works for the position control with a scan time of 1 ms and for the speed control with a scan time of 125 µs.

For throwing an object, a s-curve must be generated as it is shown in Figure 9. At first the arm must be accelerated from the angle φ = 0° during an angle $\Delta\varphi_{acc}$ to the final rotary speed ω_0 which leads to the peripheral speed v_0 of the object in the gripper. At φ_{acc} the arm must be decelerated during an angle $\Delta\varphi_{dec}$. The point

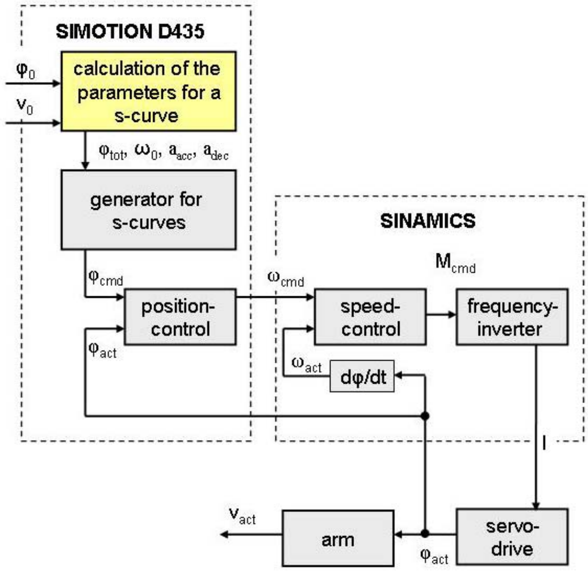


Figure 7. Functional structure of the control system for the throwing robot

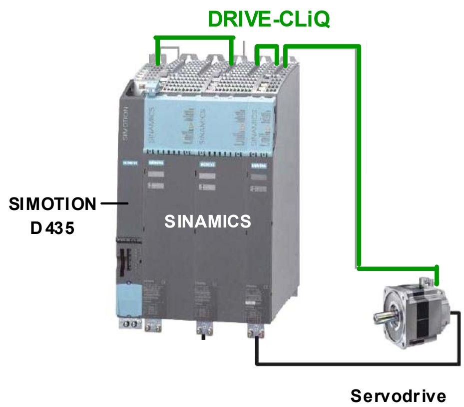


Figure 8. Hardware of the control system

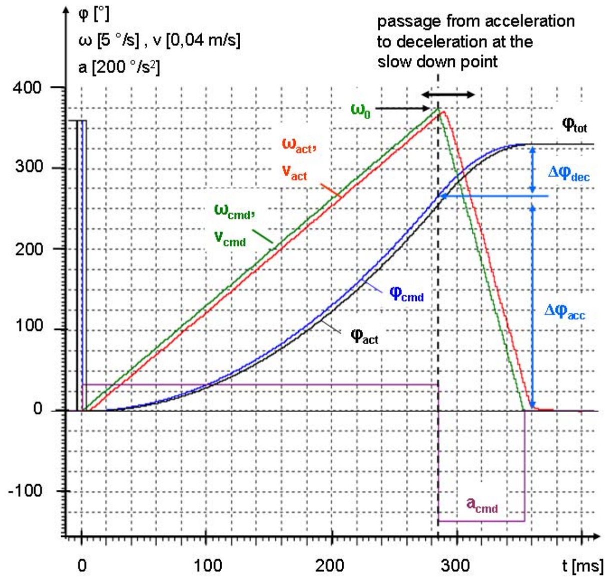
when the deceleration starts shall be named in the following as “slow down point”.

For the acceleration the values can be calculated with the following equations:

$$\Delta\varphi_{acc} = 270° + \alpha_0 - \Delta\varphi_{corr} \tag{8}$$

$$\varpi_0 = \frac{360° \cdot v_0}{2\pi \cdot r_{arm}} \tag{9}$$

$$a_{acc} = \frac{\varpi_0^{\ 2}}{2 \cdot \varphi_{acc}} \tag{10}$$



φ_{cmd} , φ_{act} - angle of the arm (command value, actual value)
ω_{cmd} , ω_{act} - rotary speed of the arm
v_{cmd} , v_{act} - peripheral speed of the gripper
a_{cmd} - rotary acceleration

Figure 9. Characteristics of the variables for a throw

In equation (8) $\Delta\varphi_{corr}$ is a correction value. It is required since the object to be thrown doesn’t leave the gripper immediately, when the arm has reached the slow down point. Depending on the geometric dimensions of the gripper, the value of the rotary speed ω_0 and the value of the deceleration a_{dec}, the object releases from the gripper later.

For the deceleration always the same value a_{dec} = 15,514.21 °/s² is used. Related to the gripper which moves on a circle with r_{arm} = 460 mm this is a deceleration of about 125 m/s². The angle for the deceleration can be calculated as

$$\Delta\varphi_{dec} = \frac{\varpi_0^{\ 2}}{2 \cdot a_{dec}} \tag{11}$$

So the total angle of the arm for a throw is

$$\varphi_{tot} = \Delta\varphi_{acc} + \Delta\varphi_{dec} \tag{12}$$

The throwing robot shown in Figure 6 allows for objects with masses m < 100g speeds of throwing with a maximum of $v_{0,max}$ = 25 m/s.

5. Measurements

The accuracy of the throwing robot was verified with two series of measurements:

- Series 1:
  25 experiments were performed where the same tennis-ball with a diameter of d = 64 mm and a mass of m = 56 g was launched with v_0 = 10 m/s and α_0 = 28°.

- Series 2:
  25 experiments were performed where the same tennis-ball, as it was used in series 1, was launched with v_0 = 15 m/s and α_0 = 24°.

5.1. Measurements at the motor shaft

At first the accuracy of the rotary axis was analyzed with a test function, which is provided by the motion control. It can trace internal variables every 1 ms. With this function the characteristics of the command angle φ_{cmd}, the actual angle φ_{act}, the command speed ω_{cmd} , the actual speed ω_{act} and the command acceleration a_{cmd} of the rotary axis were recorded as it is shown in Figure 9. With the speeds ω_{cmd} and ω_{act} also the characteristics of the peripheral velocities of the gripper can be calculated as follows:

$$v_{cmd} = \frac{2 \cdot r_{arm} \cdot \pi}{360°} \cdot \varpi_{cmd} \tag{13}$$

$$v_{act} = \frac{2 \cdot r_{arm} \cdot \pi}{360°} \cdot \varpi_{act} \tag{14}$$

In all experiments of both measurement series the passages at the slow down point from the acceleration to the deceleration were investigated in detail. It was found that the deviations of the actual angles and the actual speeds from one throw to the others were always extremely little ($\Delta\varphi_{act}$ < 0.01° and Δv_{act} < 0.01 m/s). Since these values were measured with the encoder which is integrated in the drive, they give of course only information about the accuracy at the shaft of the drive.

5.2. Measurements of launches

To get information directly from the launches of the objects a high-speed camera was used. All experiments of both measurement series were recorded with this camera. The images of the launches were assembled to trajectories as it is shown in Figure 10. Therewith the angles of throwing α_0 could be determined directly. In both measurement series a maximum difference from one throw to the others of $\Delta\alpha_0 \approx 1°$ was observed. To these measurements however it must be stated that the angles could be determined by this method only with an accuracy of about 0.3°.

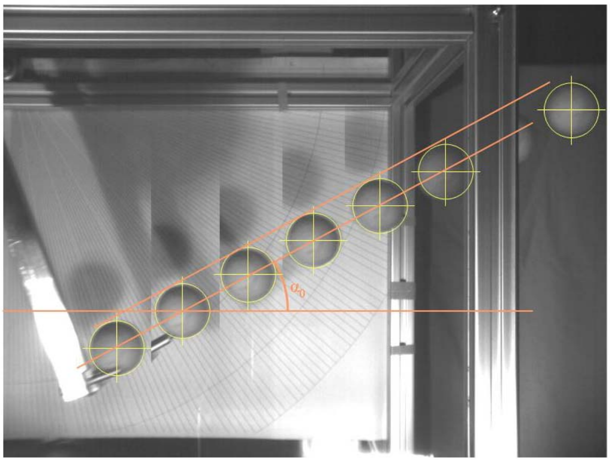


Figure 10. Trajectory after launching a tennis-ball with α_0 = 28° and v_0 = 10 m/s. The positions of the tennis-ball are shown every 10 ms

5.3. Measurements at the target points

To measure the accuracy of the throws directly at target points, a piece of a pipe with a diameter d was mounted as a target in a certain distance x_T and in a certain elevation y_T from the throwing robot as it is shown in Figure 11.

For the measurement series 1 a pipe with d = 120 mm was mounted at x_T = 3 m and y_T = 1.01 m. All 25 thrown tennis balls flew directly through the pipe. Therewith it can be stated that the trajectories had in this measurement series a deviation in the elevation of $|\Delta y_T| < 30$ mm.

For the measurement series 2 a pipe with d = 250 mm was mounted at x_T = 8 m and y_T = 1.7 m. In the tests 23 from 25 thrown tennis balls flew directly through the pipe. Therewith it can be stated that the trajectories in this measurement series had a deviation in the elevation of $|\Delta y_T| \lesssim 100$ mm.

6. Conclusions and future work

A 1-DOF-throwing robot with a rotary axis was presented. With this robot it is possible to throw objects

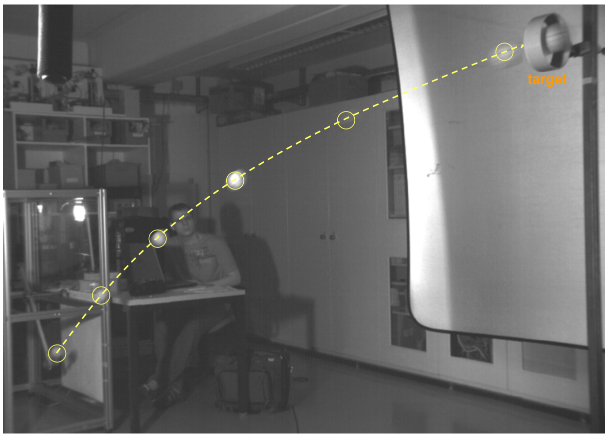


Figure 11. Trajectory of a tennis-ball through a pipe as a target.

with masses of up to 100 g in a distance of 8 m into elevations of up to 8 m. The accuracy of this device was verified in two measurement series by throwing tennis balls over different distances. In the next step this device shall be used to throw axial symmetric objects. One challenge for this application is, to develop a gripper, which releases the objects at launching without causing a rotational movement to them.

7. Acknowledgement

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References

[1] H. Frank, N. Wellerdick-Wojtasik, N. B. Hagebeuker, G. Novak, S. Mahlknecht, “Throwing Objects - A Bioinspired Approach for the Transportation of Parts”, *Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics (ROBIO),* December 17- 20, 2006, Kunming, China, pp. 91 - 96.

[2] H. Frank, D. Barteit, F. Kupzog, “Throwing or Shooting - A new Technology for Logistic Chains within Production Systems”, *Proceedings on 2008 IEEE International Conference on Technologies for Practical Robot Applications,* 10 -11 November, 2008, Woburn, MA, USA.

[3] U. Frese, B. Bäuml, S. Haidacher, G. Schreiber, I. Schaefer, M. Hähnle, G. Hirzinger, “Off-the Shelf Vision for a Robotic Ball Catcher”, *Proceedings of the 2001 IEEE International Conference on Intelligent Robots and Systems,* October 29 – November 3, 2001, Maui, Hawaii, USA.

[4] A. Namiki, M. Ishikawa, “Robotic Catching Using a Direct Mapping from Visual Information to Motor Command”, *Proceedings on 3rd IEEE International Conference on Robotics and Automation,* September 14 - 19, 2003, Taipe, Taiwan, pp. 2400 – 2405.

[5] H. Frank, D. Barteit, M. Meyer, A. Mittnacht, G. Novak, S. Mahlknecht, “Optimized Control Methods for Capturing Flying Objects with a Cartesian Robot”, *Proceedings on 3rd IEEE International Conference on Robotics, Automation and Mechatronics,* September 22-24, 2008, Chengdu, China.

[6] D. Barteit, H. Frank, F. Kupzog, “Accurate prediction of interception positions for catching thrown objects in production systems”, *Proceedings on 6th IEEE International Conference on Industrial Informatics*, July 13-16, 2008, Daejeon, Korea, pp. 893-898.

[7] Herbert Hähnchen GmbH, „Hochgeschwindigkeits-zylinder, von 0 auf 30 m/s mit 850 g“, www.haehnchen.de, Aug. 2008.

[8] F. Trieb, „Wasserstrahlschneiden - Grundlagen und praktische Anwendungen. Waterjet cutting - basics and practical applications“, *ICCT, International Conference on Cutting Technology,* Kontec Gesellschaft für technische Kommunikation, 2002, Hamburg, pp. 8 – 14.

[9] T. Senoo, A. Namiki, M. Ishikawa, “High Speed Throwing Motion Based on Kinetic Chain Approach”, *Proceedings on IEEE International Conference on Intelligent Robots and Systems,* Sept, 22-36, 2008, Nice, France, pp. 3206 – 3211.

[10] H. Frank, “Design and Simulation of a Numerical controlled Throwing Device”, *Proceedings of the 2008 Asia International Conference on Modelling and Simulation,* May 13 – 15, 2008, Kuala Lumpur, Malaysia, pp. 777 – 782.

[11] H. Frank, “Determination of Launching Parameters for Throwing Objects in Logistic Processes with Direct Hits”, *Proceedings on 13th IEEE Conference on Emerging Technologies and Factory Automation*, 15 – 18 September, 2008, Helmut-Schmidt-University Hamburg, Germany.

[12] P.S. Chudinov, “An optimal angle of launching a point mass in a medium with quadratic drag force”. http://arxiv.org/ftp/physics/papers/0506/0506201.pdf

[13] J. Dunlop, “Free Flight Aerodynamics of Sports balls”, Acousto-Scan, Aug 15, 2003.