

# ANALYSES OF AIR FRICTION EFFECT ON THE MOTION SYSTEM CONTROL

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## Introduction

The article deals with modified existing model of “mechanical ball juggler”, which includes the effect of the air friction. The papers describe a mathematical model of a transversal throw with the friction effect. The air friction mainly takes affect on the flying object – ball. This fact is directly involved in Master generator, whose task is to generate a desired vector of waveforms for the system control

## Introduction

The article deals with analyses of air friction on the fast dynamic motion system whose task is to juggle in x,y surface. The system which is powered by one servo drive is described in the article, and the center of the arm rotation is symmetrical on both sides of the juggling shoulders. The basis of the control for this system is Master-Slave control, with well-known limits of the desired waves-forms of the Master generator. The parameters for the Master generator can be designed on two different ways which are in detail described in the section “the design of the juggling algorithm”. The visual feedback information by video recording of the motion system is one of the possible ways how to get feedback information about a juggling object, because these kinds of systems are open loops systems without actual information about flying objects. The application for visual feedback which we use for monitoring this system is described in [1]. Few experiments are shown in the section “Experiments”, which compare a juggling algorithm without an effect of the air friction to the model which counts the air friction on the flying juggling object.

## I The system specification

The whole system is controlled by PC, by using program Matlab/Simulink. The communication card MF624 is installed on PC board and program Matlab can communicate with this card using the Real Time Toolbox. DGV700 frequency converter can be configured to accept external torque reference provided by communication MF624 card. This card is also used to process the feedback position signal from the converter which indicates the actual juggler shoulder position. [2]

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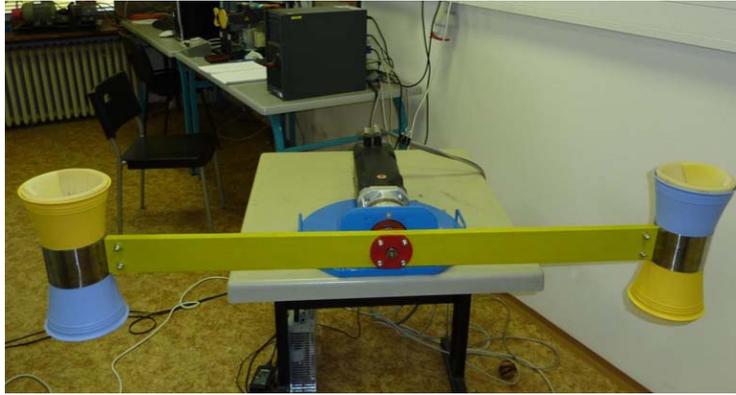
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The juggler system is controlled by position controller. We used the pole-placement method to design parameters of the regulator. The input to the system is given by 4D master generator. The role for Master generator is to generate desired waveforms signals to throw the ball with the arm with desired velocity and acceleration from a desired angle, and a generate signal to catch the flying ball. The state variables for 4D Master are position, velocity, acceleration and jerk.

$$\bar{V}^* = \left[ \varphi^* \quad \frac{\partial \varphi}{\partial t} = \omega^* \quad \frac{\partial \omega}{\partial t} = \varepsilon^* \quad \frac{\partial \varepsilon}{\partial t} = \tau^* \right]$$

The juggler system is shown in Fig. 1



**Fig.1** 1 DoF. Juggling system

## II The design of the juggling algorithm

The model of the juggler system is based on the theory of the ballistic trajectory. In an ideal surface the equations for the motions can be described by using Newton's II law of motion (1) or Lagrange – Euler motion equations (2).

II Newton motion law:

$$m \frac{d^2 \bar{r}}{dt^2} = \bar{F} + \bar{G} \quad \begin{array}{l} x: m \frac{d^2 x_T}{dt^2} = m a_x \\ y: m \frac{d^2 y_T}{dt^2} = m a_y + mg \end{array} \quad (1)$$

Lagrange – Euler:

$$\begin{array}{l} x: \frac{d}{dt} \frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x} = m \ddot{x} \equiv 0 \Rightarrow \ddot{x} = 0 \\ y: \frac{d}{dt} \frac{\partial L}{\partial \dot{y}} - \frac{\partial L}{\partial y} = m \ddot{y} - m \bar{g} \equiv 0 \Rightarrow \ddot{y} + \bar{g} = 0 \end{array} \quad (2)$$

In these equations the effect of the air friction on the flying object was not taken into account

By solving these two equations from (1) or (2) we get the actual ball position and the velocity of the flying ball.

$$x(t) = \int v_x dt = |v| \cdot \cos(\varphi) \cdot t$$

$$y(t) = \int v_y dt = |v| \cdot \sin(\varphi) \cdot t + \frac{1}{2} \cdot g \cdot t^2 \quad (3)$$

In Fig. 4 we can see the way to calculate the set up master to throw ball with desired velocity in defined angle.

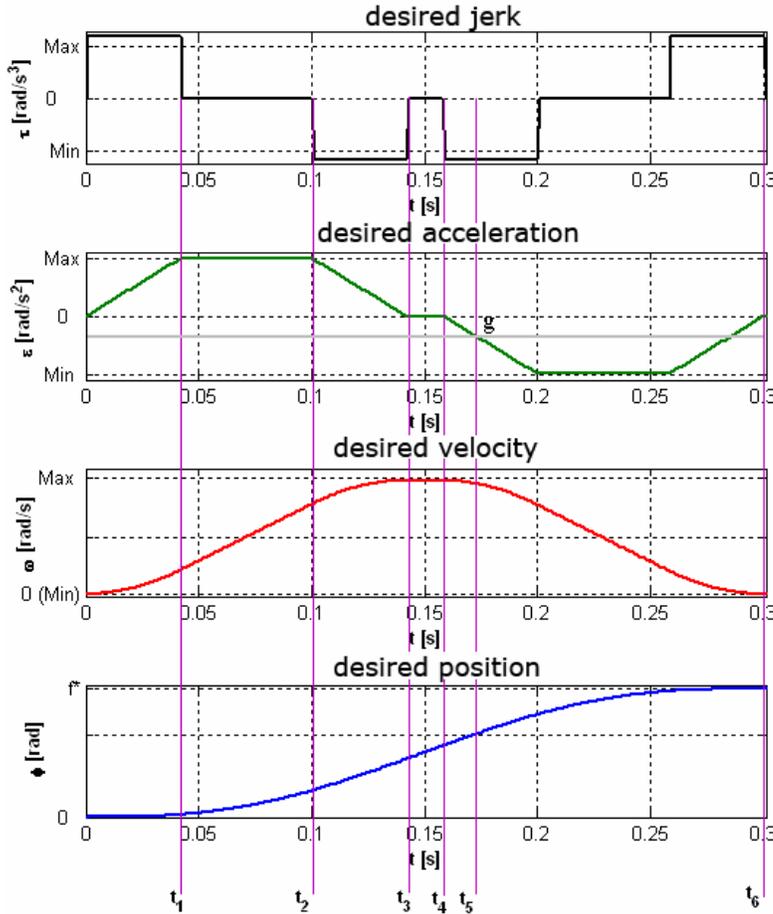


Fig. 2 setting up the master generator

$$t_1 = \frac{\epsilon_{max}}{\tau_{max}}$$

$$t_2 = \frac{\omega_{max}}{\epsilon_{max}}$$

$$t_3 = t_1 + t_2$$

$$t_4 = \frac{\varphi^* - 2\varphi_3}{\omega_{max}} + t_3$$

$$t_5 = \frac{\epsilon_{45}}{-\tau_{max}} + t_4$$

$\epsilon_{45} = -g$

The arm movement can be divided into six parts:

- The first part  $0 \leq t \leq t_1$ , arms start to move (start to accelerate)
- The arm moves with constant acceleration  $t_1 \leq t \leq t_2$   $\epsilon = \epsilon_{max}$
- Setting time to maximum velocity  $0 \leq t \leq t_1$ ,  $\omega_{34} \leq \omega \leq \omega_{max}$
- Moving with constant velocity  $t_3 \leq t \leq t_4$   $\omega = \omega_{max}$
- The throwing ball time, and throwing angle  $t = t_5$ ;  $\varphi = \varphi_5$
- Desired master angle setting  $\varphi = \varphi^*$

The ball has left the basket in the time when the arm starts to accelerate in reverse direction to set the desired position, when generator is set on value  $\epsilon = -g$ ,  $\varphi = \varphi_5$ .

The desired master angle can be set as:

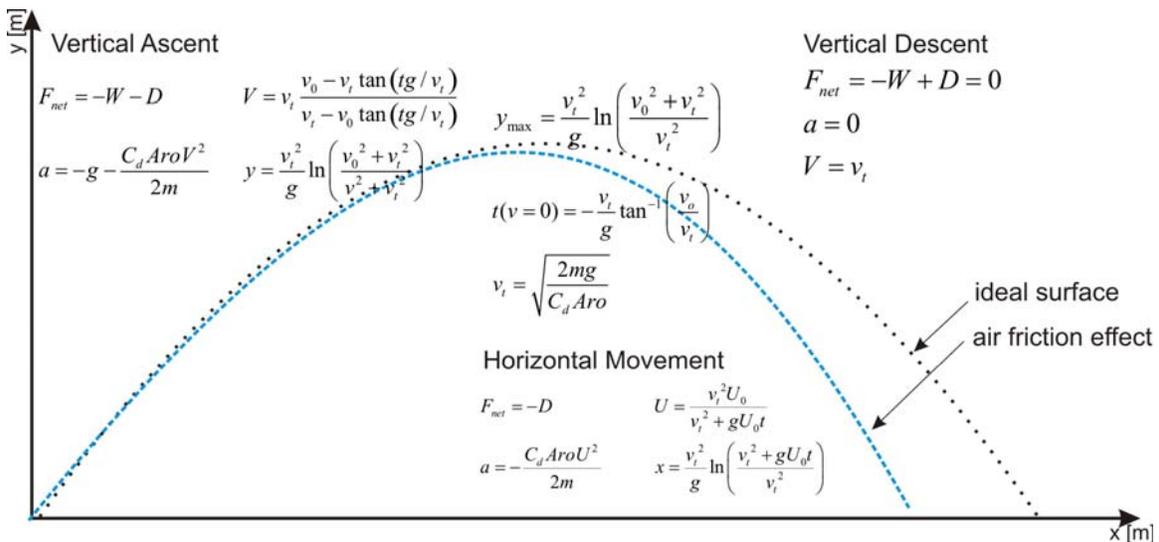
$$\varphi^* = \varphi_5 + (\varphi_3 - \varphi_{45}) \quad (4)$$

Or:

$$\varphi^* = 2\varphi_3 + \varphi_{34} \quad (5)$$

The way how to set up the parameters of Master is in detail described in reference [2] and [3].

In the equations (1), (2) and (3) it is not mentioned the dragging effect of the air on the flying object, this case can exist only in an ideal surface. In a real surface there are more factors which cause flying trajectory of the thrown object. One of the factors which has mainly effect on the trajectory of the flying object is the air friction. The definition of the air friction effect on the flying object can be simply described by Fig. 3



**Fig. 3** Air friction effect

At launch the ball is inclined at some angle to the vertical, so we resolve the initial velocity into a vertical and horizontal component. Unlike the ballistic flight equations, the horizontal equation includes the action of aerodynamic drag on the ball. In the vertical plane, the only forces acting on the ball are the forces of weight and drag. There is a characteristic velocity which appears in many of the equations that is called the terminal velocity -  $v_t$ , because it is the constant velocity that the object sustains during a coasting descent. During the vertical descent, for a light object, the weight and drag of an object are equal and opposite. There is no net force acting on the ball and the vertical acceleration is zero [4].

In the Fig. 3 are shown basement equations which are used to describe ballistic curve by mathematical relationship. Symbols and their units form movement equations are:

$a$  – acceleration [ $m/s^2$ ]

$m$  – mass [ $kg$ ]

$W$  – weight [ $kg$ ]

$C_d$  – drag coefficient <0-1>

$W$  – weight [ $kg$ ]

$g$  – gravity acceleration [ $m/s^2$ ]

$A$  – cross-sectional area of the ball [ $m^2$ ]

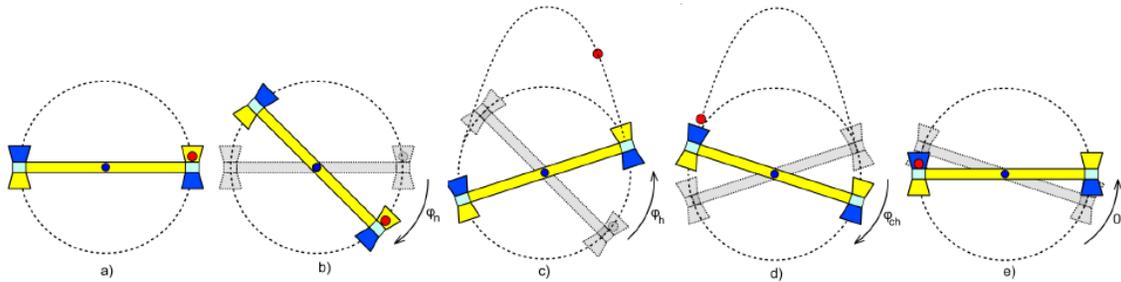
$\rho$  – density [kg/m<sup>3</sup>]

Drag “D” can be expressed as: 
$$D = \frac{1}{2} C_d \rho A v_t^2 \tag{4}$$

The movement equations for ballistic trajectory from Fig. 3 including the drag effect of the air friction are expressed from Newton’s II low of motion. Explanations of movement equations and step by step expressions to the final equations can be found in literature [4].

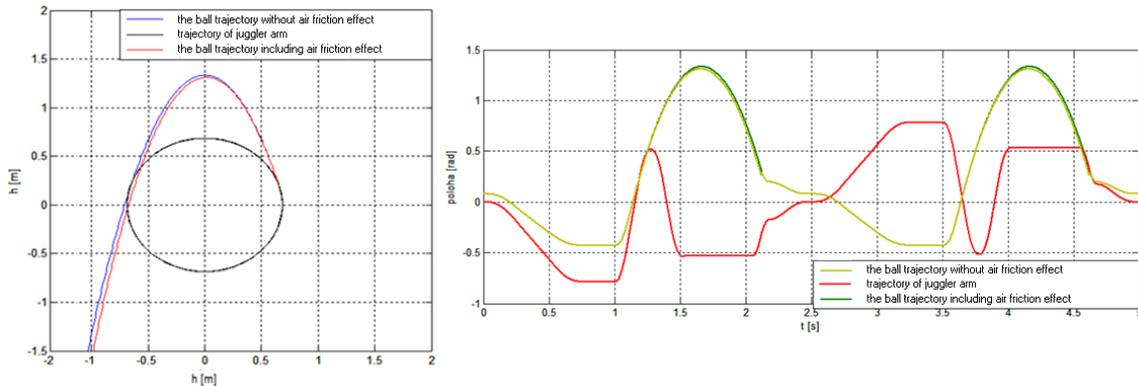
### III Experiments

The designed juggling algorithm was based on the movement equation from section II. This algorithm was tested on the virtual model and a real system, the results were compared to each other. The results from the simple juggling algorithm which is shown in Fig.3 will be presented in this section. The simple juggling algorithm worked in this way: the ball was thrown by one arm from one side of the juggling system and caught on the other side with the other arm, and reverse.



**Fig. 4** Simple juggling algorithm

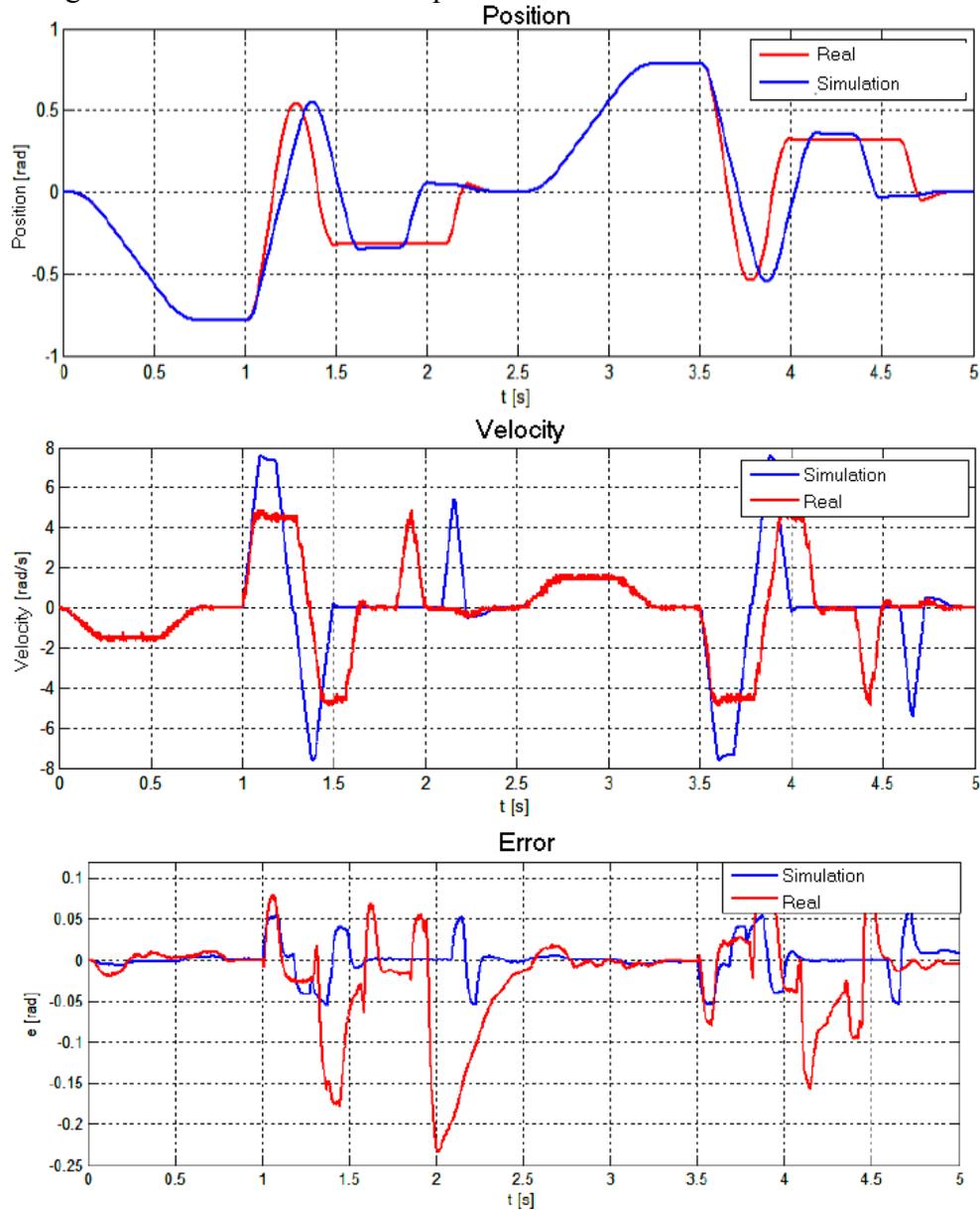
Comparing the models to each other is shown in Fig 5. On the left side in Fig. 5 is shown the juggler area with a black circle. The angle of the throwing ball was the same in both models. The angle of catching the ball was a bit bigger in the model which includes the air friction.



**Fig. 5** Comparing the models

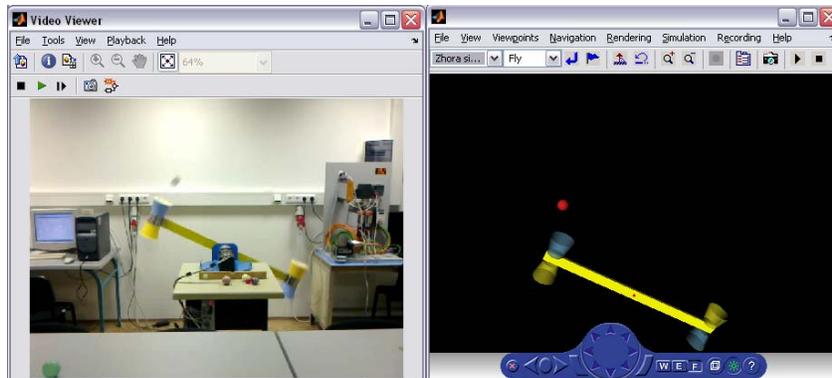
The actual position of the ball on y axis with time t relation is shown on the right side in the same figure

The same experiment was tested on the real system. Comparing the model to the dragging and the real system is shown in Fig. 6. The arm position of the juggler system is shown on the top graph, the actual velocity of the arm is the second graph, and the final third graph is regulation error – the difference between the desired position generated by the Master generator and the actual arm position.



**Fig. 6** Comparing the simulations and the real system

The juggling was recorded by a web camera, and by the utility created in Matlab/Simulink streaming video from the web camera can be compared to by virtual model made in Simulink.



**Fig. 7** Utility which compares video stream to virtual model

More information about this utility and the way how it works was presented in [1].

## Conclusion and future work

The results in this article are shown from the virtual model of “ball juggler system” and compared to the results from the real system. The virtual model was based on the mathematical equations which describe motions of the ball by ballistic trajectory. The results from the model which include an effect of the air friction are a bit closer to the real system as the model without the air friction effect. The differences between the model and the real system can be caused by other factors occurred in the system (filling of the baskets, dumping of the ball, etc.). The visual feedback is one of possible ways how to get the information about the actual position of a juggling object. We use a web camera as a visual feedback but only for monitoring purpose. The future plan is to design the Master generator which will automatically generate the desired wave forms from the information given by a visual feedback.

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