The control of the ball juggler

S.Triaška, M.Žalman

Abstract — The ball juggler is a mechanical machinery designed to demonstrate the possibility of juggling with a servo drive. The position control of the servo drive with a juggler arm is the base of the whole system. The juggler is a movement system with one degree of freedom with the possibility of juggling with one ball. Our work in these papers is focused on description of the juggler system and the possibility to design the position control of the juggler arm and juggling algorithms.

***Key words* — Master signal generation, the juggling, position control, feedforward controller, DOF –Degree Of Freedom**

I. Introduction

THE servo drive systems are commonly used in industrial application, robotics manipulator, etc., and less used in attractive way such as ball juggler. Juggling with the servo drive is very interesting and very difficult indeed. Requirements of the application like this, are synchronized, repeatable movements of high speed and precise control. Juggling can be realized with one or more balls, in two or three axis. Considering the controlling system and DOF, the jugglers and the juggling algorithm are different. The juggling system with three balls and the possibility of controlling the system like this is described in details in "Visual-Feedback Juggler With Servo Drives" [1]. Other examples of jugglers manipulator are paddle juggling of the ball by racket and "pushing and hitting manipulator", which are described in [2] and [3] references. The method of the juggling, algorithm and how juggling algorithm works is described in details in the papers "The Science of Juggling" [6], but none reference is focused to toss and catch the ball with only one servo drive system.

These papers describe a method of juggling with the servo drive system to juggle with one ball in one DOF (xy surface). The juggler is designed with a juggling arm, whose task is to throw a ball, and catch the flying ball. The ball juggler system is powered by one servo drive.

The papers are organized as follows:

Physical and mechanical proportions of the ball juggler are described in section II.

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The control implementation of the whole movement system is described in section III. The ball tracking regulation is based on the control position which is part of this section.

The juggling algorithms and juggling measurements are included in section IV of the article.

Our work in this article includes and focuses on the following areas:

- Identification of the juggler parameters, the moment of inertia of the whole system (the servo drive with juggling arm).
- Controlling the system, feedforward control.
- Kinematics model of the juggling algorithm applied in this work.

Some topics for the future work with the juggling system are shown at the end of the article.

II. System description

The image of the ball juggler is illustrated in the figure 2. The ball juggler is a positional movement system with one DOF. The whole system consists of six separate devices which are connected between each other.

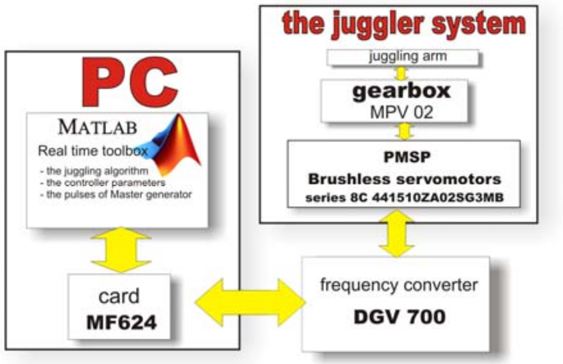

Fig.1 The block diagram of the system

The juggler system is controlled by PC. DGV700 frequency converter can be configured to accept external torque reference signal which is provided by MF624 interface card installed on PC. The MF624 card is also used to process quadratural position signal from the converter which indicates the actual juggler arm position. The information about the position is given by the resolver which is a part of the drive. We don't have any resolver interface card, so we decided to use interface which is built in the frequency converter. This interface can emulate the incremental encoder–like the signal on its output. The drive shaft is connected with MPV 02 planetary gearbox. The transmission of the planetary gearbox is 1:10, it means that the shaft of the servo drive is ten times faster than the shaft of the planetary gearbox.

The juggling arm with the ball holders-baskets is constructed on the planetary gear.

The torque of DGV700 frequency converter can be configured and controlled of analog value of ±10V from the program Matlab/Simulink using The Real Time Toolbox, through the MF624 card. Communication between MF624 card and DGV700 frequency converter is provided by RS232 communication bus.

The juggler system placed on the table is shown in the figure 2, (servo drive, gearbox and juggler arm with ball holders-baskets), DGV700 frequency converter is placed under the table, the controlling PC is placed on the next table. The PC is connected with frequency converter through the MF624 card.
The table with the juggler is higher than the juggler arm which gives us options to use a juggling algorithm with 360º rotation of the juggler arm.

Fig.2 The juggler system

III. CONTROL IMPLEMENTATION

We made the model of the ball juggler in the Matlab program. To design the model we have to know all the parameters of the real plant. The parameter which mainly affects the stability of the whole system is the moment of inertia. The value of the moment of inertia of PMSP Brushless servomotors series 8C 441510ZA02SG3MB is given in servo data sheet. In data sheet you can find out all the servo drive parameters and the servo drive constrain.

- Moment of inertia

To design a model of the system it is necessary to calculate a moment of inertia of servo drive connected with juggling arm and ball holders. In the figure 3 the juggler arm is shown as well as the juggler workspace by dotted line. The axis of the arm rotation is located in the middle of the juggler arm. The final moment of inertia is the sum of all the moments of inertia that appeared in the system.

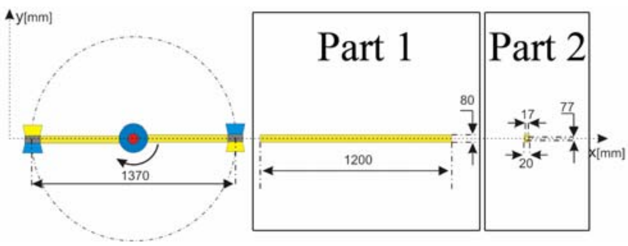

Fig.3 The juggler arm

The moment of inertia of ball holders - baskets we calculated, as a property dots which rotate around axes of rotation with radius vector r.

$$J_{arm} = J_P + 2.J_b = J_P + m_k r^2 \quad (3.1)$$

The moment of inertia of the system is the sum of the separate moments of the inertia: the moment of inertia of the servo drive shaft, the moment of inertia of the reducer (the gearbox) and the moment of inertia the juggler arm, is divided by square ratio size of the gearbox.

$$J = J_M + J_G + \frac{J_{arm}}{i^2} \quad (3.2)$$

The parameter of the moment of inertia the gearbox shaft (MPV 02) is taken from the data sheet.
The world coordinates system x,y,z is fixed to the arm joint.

J_p - The moment of inertia of arm without basket

J_b - The moment of inertia of the basket

$x_{1/2}, y_{1/2}, z_{1/2}$ - coordinate of the parts

$m_{1/2}; \rho_{1/2}$ - The mass of the part, specify the density of the material

- Control of the juggler position

The juggler system is controlled by PIV controller. Input to the system is given by 4D master generator, whose task is to generate signal to throw the ball with the arm, and generate signal to catch the flying ball. Controlling with 4D master generator is called feedforward control. The base feedforward (Master-Slave) control can be classified as stock control or control through the model. Master-Slave structure with well-set generator of state variables and well-chosen and tuned controlled structure provide high quality of controlling movement and changing some system parameters (e.g. moment of inertia) and reduces impact of shock moments in the mechanical part of the machine even when using highly nonlinear transmission mechanisms.

Master:

- The generator of controlling system variables
- The vector of control may have more components than the number of measurable parameters
- The generator of vector control is implemented on a feedback algorithm

The task of master generator is to generate the desired waveforms of state variables to make the juggling algorithm.

The juggler control can be separated in three different parts.

- The first part is defined to swing with the arm to the starting point.
- The second part is defined to accelerate the arm and break the movement
- The third part is defined to decelerate the juggler arm and to catch a flying ball.

Model of the juggler

The input to the system is a desired rotation shaft – position. The sensor of position is placed on the output of the system. The resolution of position sensor is 4096 pulses/revolution. The feedback information about the actual position to the system comes from the sensor. We don't have any feedback information about the actual position of the ball.

A block diagram of the mechanical ball juggler with PIV position controller and feedforward controller is shown in the figure 4.

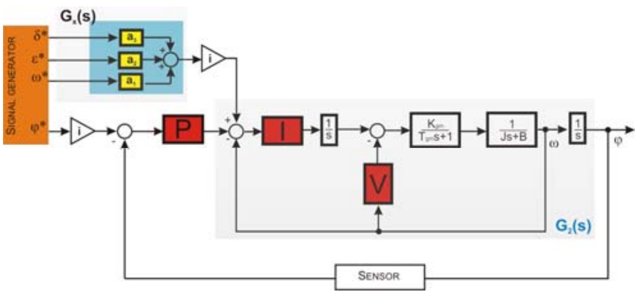

Fig.4 The block system diagram of the model

The transfer of closed control circuit is given by:

$$G(s)=\frac{M(s)}{N(s)}=\frac{\frac{K_{GM}.I.P}{J}}{s^3+\frac{B+V.K_{GM}}{J}s^2+\frac{K_{GM}.I}{J}s+\frac{K_{GM}.I.P}{J}} \qquad (3.3)$$

Because of its fast dynamics, the transfer function of the torque generator we replaced as one:

$$GM=\frac{1}{T_{gm}s+1}=1 \qquad (3.4)$$

The method of pole-placement is one of possible methods to design parameters of PIV controller. This means that by desired dynamics of system we choose the poles of the characteristic polynomial. By comparing the characteristic equation of closed control circuit of the actual transfer (3.3) and the transfer of the desired polynomial (3.5) in the same square we get parameters of the regulator (3.7).

The transfer of the desired dynamics of the system:

$$Gz(s)=\frac{M_0(s)}{N_0(s)}=\frac{k\omega_0^{\,3}}{\left(s^2+2\xi\omega_0 s+\omega_0^{\,2}\right)\left(s+k\omega_0\right)} \qquad (3.5)$$

The parameters of PIV controller will be calculated from the comparison of denominator of desired and actual transmission.

$$\begin{aligned} N(s)&=N_0(s)\\ N_0(s)&=\left(s^2+2\xi\omega_0 s+\omega_0^{\,2}\right)\left(s+k\omega_0\right)\\ N(s)&=s^3+\frac{B+V.K_{GM}}{J}s^2+\frac{K_{GM}.I}{J}s+\frac{K_{GM}.I.P}{J} \end{aligned} \qquad (3.6)$$

On the final we get the parameters of the controller:

$$\begin{aligned} V&=\frac{(2.\xi+k).\omega_0.J-B}{K_{GM}}\\ I&=\frac{(2.\xi.k+1).\omega_0^2.J}{K_{GM}}\\ P&=\frac{k.\omega_0}{(2.\xi.k+1)} \end{aligned} \qquad (3.7)$$

In the simulation model we used $K_{GM}=1$.

Feedforward controlling is stated in terms of quality of controlling. It mainly affects the regulation deviation. At well-set forward-control the error should be reduced. The base of feedforward control lies in the fact that the transfer of regulatory deviation is zero.

$$G_e(s)=\frac{\varphi^*(s)-\varphi(s)}{\varphi(s)}=0 \;\Rightarrow\; G_X(s)=\frac{1}{G_2(s)} \qquad (3.8)$$

The parameter of the feedforvard controller:

$$\begin{aligned} a_1&=1\\ a_2&=\frac{B+V.K_{GM}}{K_{GM}.I}\\ a_3&=\frac{J}{K_{GM}.I} \end{aligned} \qquad (3.9)$$

The system is designed so that the master generates the state variable of the final pluck, the acceleration, the velocity and the position of the arm.

IV. JUGGLING ALGORITHM

The kinematics model of the juggling algorithm comes from parabolic curve flying object - transversal throw (shown in figure 4), which is given by equation (4.1) and (4.2) in x,y coordinates system. This system is shifted comparing to the juggling shoulder coordinates, x,y coordinates start in the moment when the movements of the arm stops, and the ball starts to leave the basket.
Initial condition of velocity of flying the ball is given by the master generator and can interpret:

$$\hat{v}_0 = v_{x0} + jv_{y0}$$
$$v_{x0} = |v|\sin(\varphi) \qquad (4.1)$$
$$v_{y0} = |v|\cos(\varphi)$$

Trajectory of axis is given by (4.2):

$$x = \int v_x dt = |v|.\cos(\varphi).t$$
$$y = \int v_y dt = |v|.\sin(\varphi).t + \frac{1}{2}.g.t^2 \qquad (4.2)$$

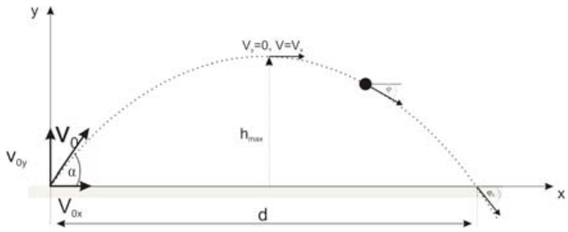

Fig.4 The transversal throw

Considering the weight of the flying object – in our case the ball, and air resistance, applying II Newton's Law of Motion we can get the movement equation of the flying object.
Juggling algorithm is shown in figure 5, and it is written in 3 steps.

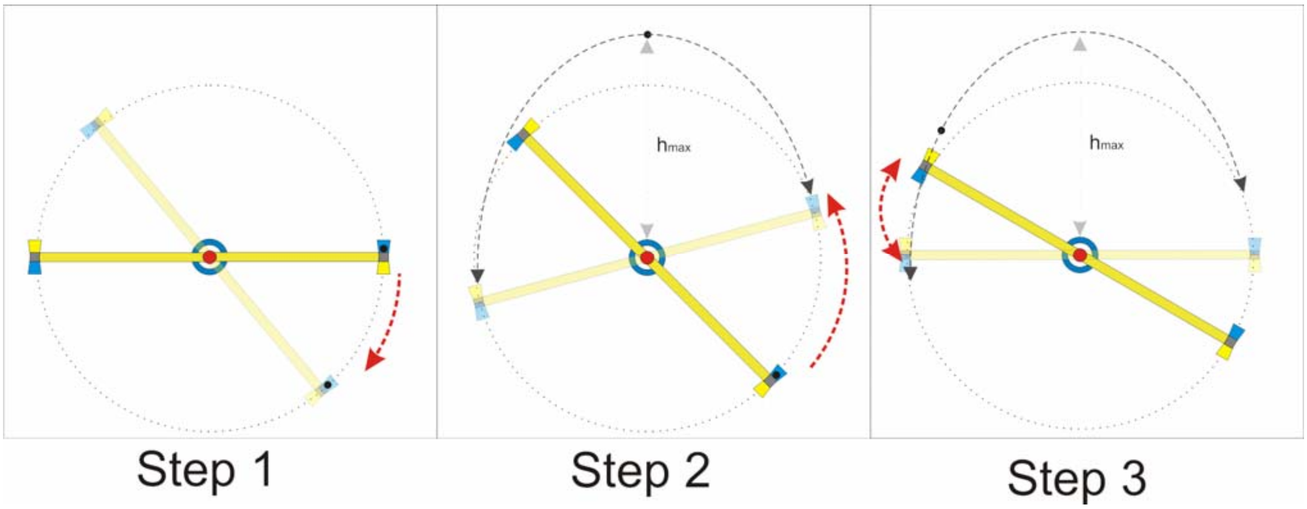

Fig.5 The juggling algorithm

The first step of the juggling algorithm shows a rotate arm with low acceleration and velocity to the starting position. The upper limits of master in this step are: $\delta = 120\left[\frac{m}{s^3}\right], \varepsilon = 5\left[\frac{m}{s^2}\right], \omega = 1.5\left[\frac{m}{s}\right], \varphi = 45[°]$.

Step 2 shows the high acceleration of the juggler arm to the position of throwing the ball (desired position), and to the moment where the ball leaves its basket. The time where arm position is the same like the desired position, the movement of the arm stops and the arm starts to move in reverse direction to catch the flying ball. $\delta = 12000\left[\frac{m}{s^3}\right], \varepsilon = 80\left[\frac{m}{s^2}\right], \omega = 5\left[\frac{m}{s}\right], \varphi = 25[°]$

Step 3 shows the moment where the arm catches the flying ball through the parabolic curve and slows down the velocity of the ball, and arrives at goal position.
$\delta = 120\left[\frac{m}{s^3}\right], \varepsilon = 5\left[\frac{m}{s^2}\right], \omega = 1.5\left[\frac{m}{s}\right], \varphi = -30(150)[°]$

We don't have any feedback information about the actual position of the flying juggling ball. The signal generator has to generate exact mathematical signal with well-known acceleration, velocity and position of the arm to tossing and catching the ball.

Controlling – desired signal given by the master is shown in figure 6.

The desired acceleration, velocity and position of the arm of a juggling period- tossing and catching the ball on both sides of the arm is shown in figure 6.

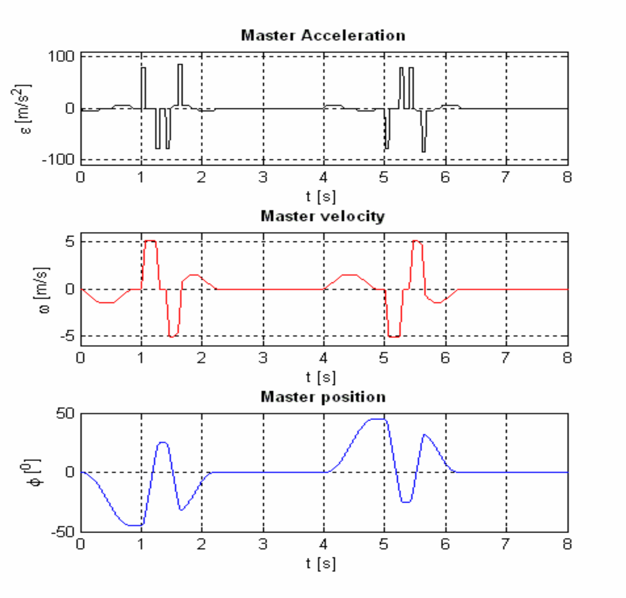

Fig. 6 Signal generator pulses

The desired signal generated in period $0 \le t \le 1$ can be compared with figure 5, step 1.
The high acceleration of the arm, the maximum size of the ball velocity, and breaking the arm movement is generated in $1 \le t \le 1.4$. The angle when the ball leaves the basket is about 25º. After this the arm starts to rotate in reverse direction to catch the flying ball.
The time when the arm catches the flying ball and stops the movement of the ball is $1.65 \le t \le 2.2$

The figure 7 shows horizontal views of the actual position of the juggling arm and the juggling ball.

The individual states of manipulator arm and flying object - the ball are shown and described in the same picture. The state of arm can be classified in five different states, the ball trace can be classified in four states.

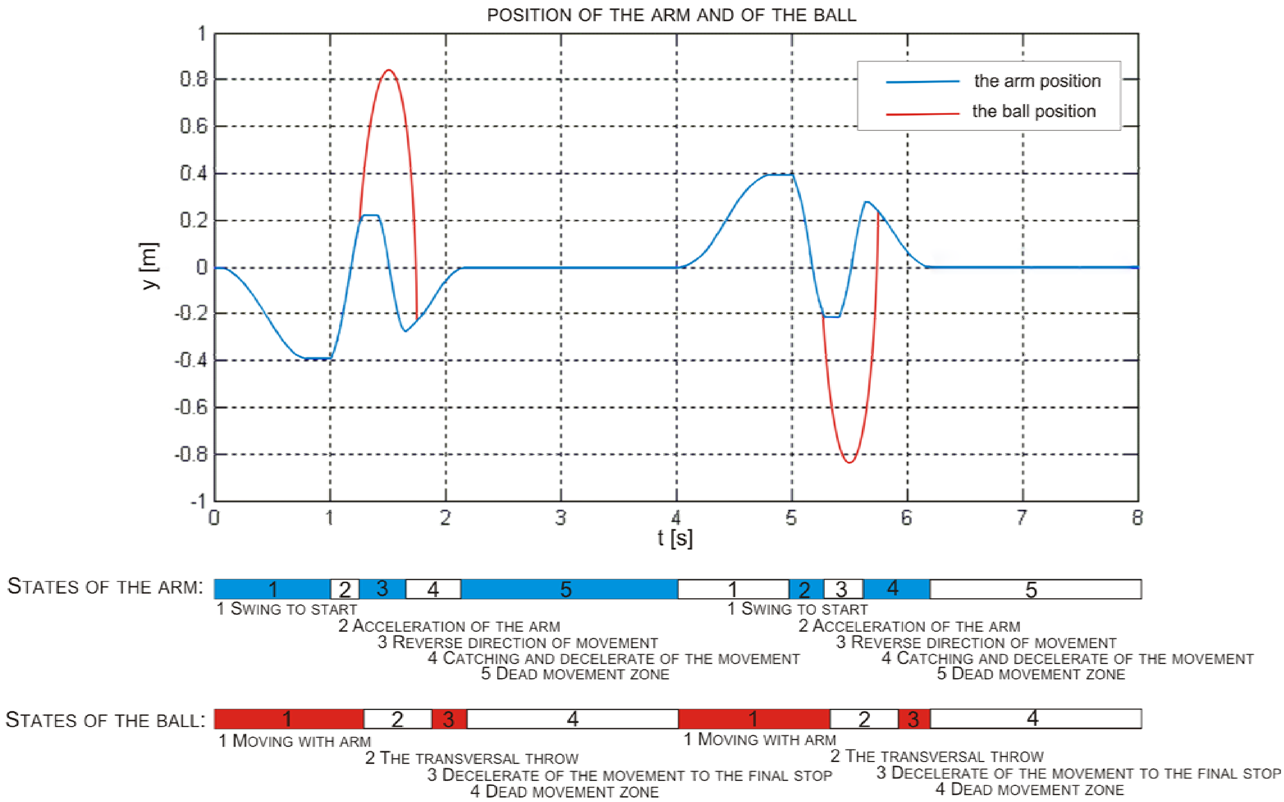

Fig. 7 Positions of the juggling arm and the juggling ball

The generate pulses are repeated periodically. The length of one juggling period is 8s. The dead movement zone between throwing from one side of shoulder and catching on the other side of shoulder to the new juggling period is 1.8s. This zone is sequently repeating after every deceleration in both directions.

V. Conclusion and Future Work

These papers describe the servo drive system with the arm, whose task is to juggle with one ball in the xy surface. In the first part of this work the whole system is described in details, the way it is connected and the way it works. The II, III and IV part are more concentrated to describe machinery and juggling algorithm, position control and feedforward control with master generator.
The advance juggling algorithms based on physics movement equations and models of these algorithms is planned in the future.
Future work will be more focused on baskets planted on juggler arm, whose task is to catch a the flying ball. The

baskets with their filling mainly effect dumping of the caught ball.

Visual feedback with the IP camera and controlling of the juggler via internet is the part of planned future work.

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