# Robotic Systems in Fast and Unstable Processes

Ing. Ľuboš Spaček, Ph.D.

Doctoral Thesis Summary

Tomas Bata University in Zlín

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Faculty of Applied Informatics

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# Robotické systémy pro rychlé a nestabilní procesy

## Robotic Systems in Fast and Unstable Processes

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# ABSTRAKT

Práca prezentuje výskum v oblasti robotických systémov riadiacich rýchle a nestabilné procesy s použitím dobre známeho modelu guľôčky na plošine ako referenčného systému. Súčasná robotika sa pomaly posúva smerom alternatívneho použitia robotických manipulátorov v oveľa viac komplexných aplikáciách. Tieto aplikácie vyžadujú väčšiu presnosť sledovania dráhy a rýchlejšiu odozvu než klasické robotické riešenia. Rýchle a nestabilné systémy poskytujú tak ideálny základ pre výskum podobných aplikácií a otvárajú nové možnosti vo využití robotických manipulátorov. Práca prezentuje pilotnú štúdiu uskutočniteľnosti v simulácii a rovnako aj reálne testy na robotickom manipulátore so 7 stupňami voľnosti.

# ABSTRACT

This thesis presents the research of robotic systems controlling fast and unstable processes using a well-known Ball & Plate model as a reference system. Current robotics is gradually shifting its aim towards alternative methods of using robotic manipulators for more complex applications. These applications require better precision, path accuracy and quicker response time than classic robotic solutions. Fast and unstable systems thus provide an ideal base for research of such applications and open new possibilities in the usage of industrial robots. The thesis presents a pilot and feasibility study in simulation and real tests on the robotic manipulator with 7 degrees of freedom.

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# 1 INTRODUCTION

Many naturally unstable processes require special attention from the point of control design because there are certain limitations that narrow the range of feasible solutions, their implementation and evaluation, as described in [1]. Most of these processes are also highly non-linear and their precise control can be a very complex problem as their behavior can dramatically change according to the particular operating point. A very convenient example of a non-linear unstable process is Ball & Plate model (hereafter abbreviated as B&P). It is a well-known multiple-input and multiple-output (MIMO) system used for educational, research and testing purposes because of its scalability, modularity, simple implementation and relatively cost-effective operation and maintenance.

It is possible to find many different designs of B&P structure (hobby, research, educational), ranging from 2 DoF (degrees-of-freedom) solutions in parallel [2, 3] or series [4, 5] configuration to 6 DoF parallel (Stewart platform) solutions [6, 7]. However, there are not many higher DoF solutions for configuration of motors connected in series (for reference see [8, 9, 10]).

So many solutions prove that the B&P system is indeed a very interesting and challenging problem to solve and the thesis will try to extend this wide range of existing solutions by using an industrial robot with two 7 DoF manipulators. Most industrial robots have 6 DoF configuration with motors connected in series because it is enough to meet most of the requirements and 7th axis is added to improve reachability and flexibility. A robotic manipulator with 7 DoF structure (Robai Cyton Gamma 300) is proposed in [8], but only last 2 axes are used for control, which essentially simplifies the solution to 2 DoF. The aim of this thesis will be to use all axes as needed and in addition, the solution with two manipulators can lead to overwhelmingly redundant 14 DoF result, which is certainly worth to exploit.

Such a quantity of mechatronic solutions of B&P model naturally leads to different approaches to control strategy. Most of the solutions use PID or state-space controllers and their different variations and optimizations (such as PD or LQR control) [2, 3, 6, 7]. Other solutions include double feedback loop structure based on fuzzy logic [11], fuzzy supervision and sliding control [12], non-linear switching [13] and H-infinity approach [14].

The feasibility of the solution in this thesis will be tested using a 2 DoF linear quadratic (LQ) polynomial controller [15]. The 2 DoF controller structure provides separation of feed-back part responsible for stabilization and disturbance rejection and feed-forward part responsible for reference tracking [16]. The polynomial approach simplifies the design problem to algebraic operations on polynomials and controller parameters are derived by minimization of the LQ criterion by calculating a spectral factorization of polynomials [15]. This type of control strategy is used because of its fast and easy implementation, reliability, relative robustness (towards system parameters change) and satisfying control results in terms of quality and precision.

# 2 CURRENT STATE OF THE PROBLEM

There are numerous works on building control strategies for robotic manipulators with standard and general methods ([17],[18],[19],[20]), but newer and more focused control strategies are still being produced ([21],[22]) by a large number of specialists in this field. This topic involves both the academic and private sectors. Numerous studies are also concerned with using robotic manipulators as a black-boxed motion mechanism for robot control relying on external inputs such as force and torque sensors (([23],[24],[25],[26]), optical sensors and cameras ([27],[28]), accelerometers, and other devices ([29],[30]). Besides this, none of the aforementioned works address the response of the robotic manipulator to unstable and relatively fast processes, despite the fact that the need for a robot to control such a process in an industrial setting may arise in the future with rapidly developing technologies such as virtual and augmented reality with tactile feedback for teleoperation of robots ([31],[32],[33],[34],[35]). Remotely-operated industrial robots are also on the rise, particularly in hazardous or remote situations like as offshore oil and gas platforms ([36],[37]). Self-motion of these robots is essential and can involve more delicate jobs supported by more sophisticated algorithms allowing for greater stability and reliability. Despite the fact that these applications do not control unstable processes, it can be assumed that their development will lead to a broader scope of applications that may require such feedback control ([31]) in processes such as polishing, grinding, or deburring in human-robot collaboration tasks or in many advanced applications requiring a non-standard approach to industrial robotic systems [38].

From the traditional 2 degrees of freedom design with actuators coupled in series [4],[5] or parallel [2],[3] configuration, to the 6 degrees of freedom parallel Stewart platform [6],[7], B&P systems can be found in educational, research, and many hobby projects. There are also various options for actuators with a higher degree of freedom, such as [8],[9],[10].

This enormous array of solutions for B&P systems demonstrates that it is a very intriguing and difficult subject to solve, and this dissertation adds to this portfolio of electromechanical structures and their control in order to achieve the objective of ball stabilization and trajectory tracking. Numerous B&P control solutions employ standard PID control or state-space controllers and its variants (PD, LQR) [2],[3],[6],[7]. A double feedback loop structure based on fuzzy logic ([11]), fuzzy supervision and sliding control ([12]), non-linear switching ([13]), and the H-infinity approach ([14]) are examples of "non-standard" solutions.

# 3 GOALS OF THE DOCTORAL THESIS

This thesis provides a preview of industrial robotic systems for controlling fast and unstable processes. A classic Ball & Plate (B&P) model will be constructed and connected to an industrial robotic manipulator as its end effector. A proper control strategy has to be chosen to not only successfully stabilize the ball on the plate and compensate for disturbances, but also to keep the controller effort within certain bounds. B&P models are mostly used at universities or in hobby projects and most of the time only during testing or measurements. However robotic systems are expected to run for long periods and fast and sharp control signals tend to invoke much larger stress on the whole system. For this reason, angular accelerations of generated plate angles (and thus those of joint angles) should be taken into consideration. Proper sensors and control HW should be also chosen.

The following goals are planned to be fulfilled in this thesis:

- To choose a suitable industrial robot for initial simulations, tests, and measurements, which is fast, safe, dexterous in motion, and easy to program and maintain.
- To make a feasibility study and pilot simulations of the robot controlling the B&P model. This should verify whether the chosen robot can perform the given task.
- To choose a suitable B&P system in accordance with the parameters of the robot, which means picking the correct size of the plate and type of the ball. There are many options and possibilities for the setup of B&P, but only one should be considered in this thesis.
- To choose a sensor for obtaining the position of the ball on the plate. This sensor should be fast and reliable enough to follow the dynamics of the B&P model, although the choice depends also on the chosen ball (or vice versa).
- To choose an appropriate control law, that can be easily implemented to the robot's (or controller's) code and is naturally able to manage the control of unstable processes such as the B&P model.
- To achieve a satisfying trajectory-tracking and path-following.

# 4 METHODS

## 4.1 System Equations of the B&P Model

The B&P system can be described by system equations derived from the general form of Euler-Lagrange equation of the 2nd kind shown in (4.1).

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_i} - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \tag{4.1}$$

where $T$ is kinetic energy of the system, $V$ is potential energy, $Q_i$ is $i$-th generalized force and $q_i$ is $i$-th generalized coordinate (position coordinates $x$ and $y$ and plate angles $\alpha$ and $\beta$).

The system for the B&P model (shown in Fig. 4.1) can be subsequently expressed as a system of 2 differential equations shown in (4.2) and (4.3). The simplified and linearized form can be seen in (4.4) and (4.5). A closer look at specific steps is described in [A.1].

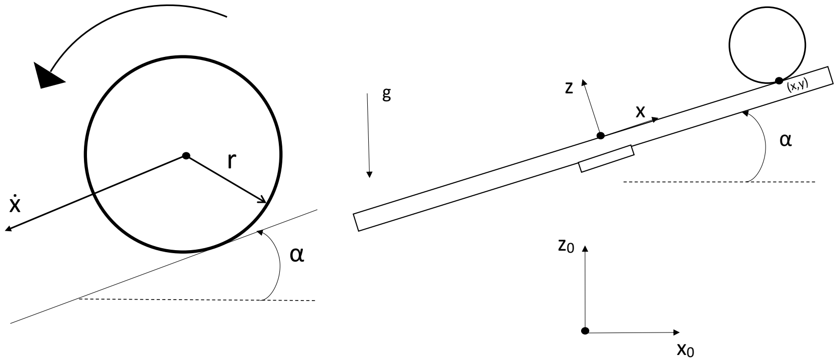

*Fig. 4.1 Ball & Plate model setup*

$$x\colon\ \left(m + \frac{I_b}{r^2}\right)\ddot{x} - m\left(\dot{\alpha}\dot{\beta}y + \dot{\alpha}^2 x\right) + mg\sin\alpha = 0 \tag{4.2}$$

$$y\colon\ \left(m + \frac{I_b}{r^2}\right)\ddot{y} - m\left(\dot{\alpha}\dot{\beta}x + \dot{\beta}^2 y\right) + mg\sin\beta = 0 \tag{4.3}$$

where $m$, $r$ and $I_b$ are mass, radius and moment of inertia of the ball respectively, $g$ is gravitational acceleration, $\alpha$, $\beta$ are plate angles ($\alpha$ changes $x$ coordinate and $\beta$ changes $y$ coordinate), $\dot{\alpha}$, $\dot{\beta}$ are first time derivatives of plate angles, $x$, $y$ are coordinates of the ball from center of the plate and $\ddot{x}$, $\ddot{y}$ are second time derivatives of ball coordinates.

$$x: \quad \ddot{x} = K_b \alpha \tag{4.4}$$

$$y: \quad \ddot{y} = K_b \beta \tag{4.5}$$

where $K_b$ is constant dependent only on the gravitational acceleration $g$ and the type of ball (whether it is spherical shell or sphere). These equations can be expressed in a continuous transfer function form (4.6) and are valid only for the dynamics of the B&P model and do not contain dynamics of the motion structure.

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_b}{s^2} \tag{4.6}$$

The resulting linearized model of B&P structure, together with approximated dynamics of the motion structure by the 1st order transfer function (with parameters $K_r$ and $T_r$) is shown in (4.7).

$$G(s) = \frac{K_b}{s^2} \frac{K_r}{T_r s + 1} = \frac{K}{s^2(T_r s + 1)} = \frac{K}{T_r s^3 + s^2} \tag{4.7}$$

## 4.2 Controller Design

The controller chosen for the study is Linear Quadratic (LQ) 2 DoF controller designed using polynomial approach. The structure of the controller is shown in Fig. 4.2 and consists of feed-forward $C_f$ and feed-back $C_b$ parts. $1/K(z^{-2}) = 1/(1-z^{-1})$ is the summation part extracted from these parts, $w(k)$ is reference value, $y(k)$ output value, $u(k)$ controller output, $G(s)$ linearized plant and $n(k)$, $v(k)$ are disturbances.

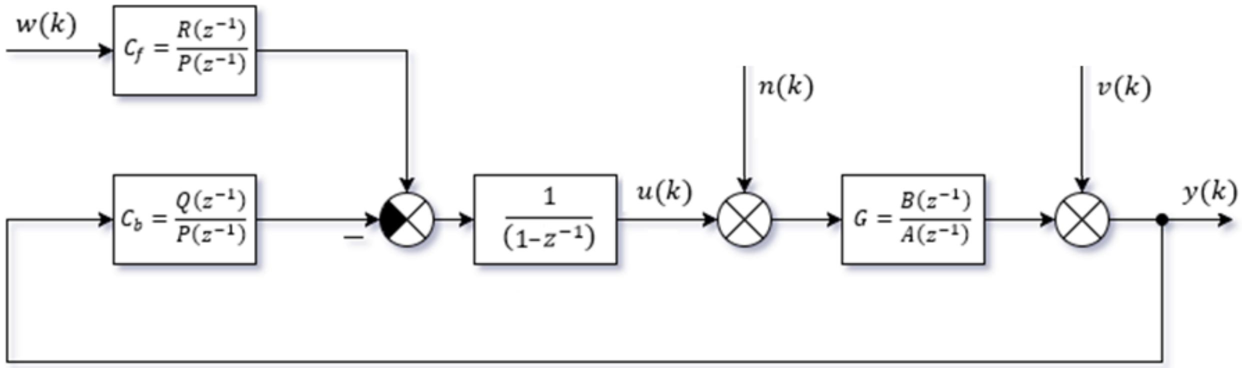

*Fig. 4.2 Structure of the 2 DoF polynomial controller*

The function (4.8) returning the output of the controller for digital implementation is derived in [A.2] for the plant described by the 3rd order transfer function.

$$\begin{aligned} u_k = (1 - p_1)u_{k-1} + (p_1 - p_2)u_{k-2} + p_2u_{k-3} + \\ + r_0w_k - q_0y_k - q_1y_{k-1} - q_2y_{k-2} - q_3y_{k-3} \end{aligned} \tag{4.8}$$

where $u_{k-i}$ and $y_{k-i}$ are outputs of the controller and plant respectively, $w_k$ is reference value and $p_i$, $q_i$ and $r_i$ are parameters of the controller (coefficients of polynomials $C_f$ and $C_b$ from Fig. 4.2).

## 4.3 Robotic System

An industrial robot is a multipurpose motion mechanism able to move an attached object in all 6 degrees of freedom, which is advantageous in the application such as B&P. The industrial robot manipulator quite suitable for B&P application is ABB IRB 14000 YuMi. YuMi (Fig. 4.3) has two manipulators with 7 DoF and 0.02 mm repeatability each. It is also a collaborative robot, which means it can safely operate without protection or external caging between the robot and humans [39]. This fact greatly reduces implementation time and simplifies testing.

ABB also offers programming and simulation environment called RobotStudio, which extends possibilities of the research, especially in the simulation part.

*Fig. 4.3 ABB's collaborative robot YuMi*

RobotStudio fully virtualizes the robot, external sensors and even provides simulated gravity, materials and friction (since RobotStudio 6.05 version), which makes it a powerful tool to exploit.

## 4.4 Position Measurement

There are several different approaches for measuring the ball on the plate. It is possible to use a camera above the plate, a touch screen on the plate or a state observer. The best way appears to be a resistive touch screen on the plate that can directly output the position of the ball on the plate without complicated calculations. It is also not statically placed in the space, but it is moved together with the plate. The resistive touch screen is also available on the market and easily maintainable or replaceable. It is also relatively robust against light and environmental conditions.

Position of the ball in the simulation environment of RobotStudio can be easily obtained using so-called Smart Components that are part of the software and provide additional control and measurement functions.

# 5 RESULTS

## 5.1 Simulated System

The Ball & Plate simulated system in RobotStudio is used and evaluated in this chapter. Controller parameters are determined, implemented and evaluated.

### 5.1.1 B&P Robotic System Identification

Dynamic parameters of the robot are not precisely known, thus identification of the system as a whole is the only option even in simulation (and can be called pseudo-identification). The whole robot is identified for the structure of the plant described in chapter 4.1 in equation (4.7). This equation approximates the whole motion structure by 1$^{\text{st}}$ order dynamic system which may seem an oversimplification to some extent, but as seen from the results this approximation is still valid for this case.

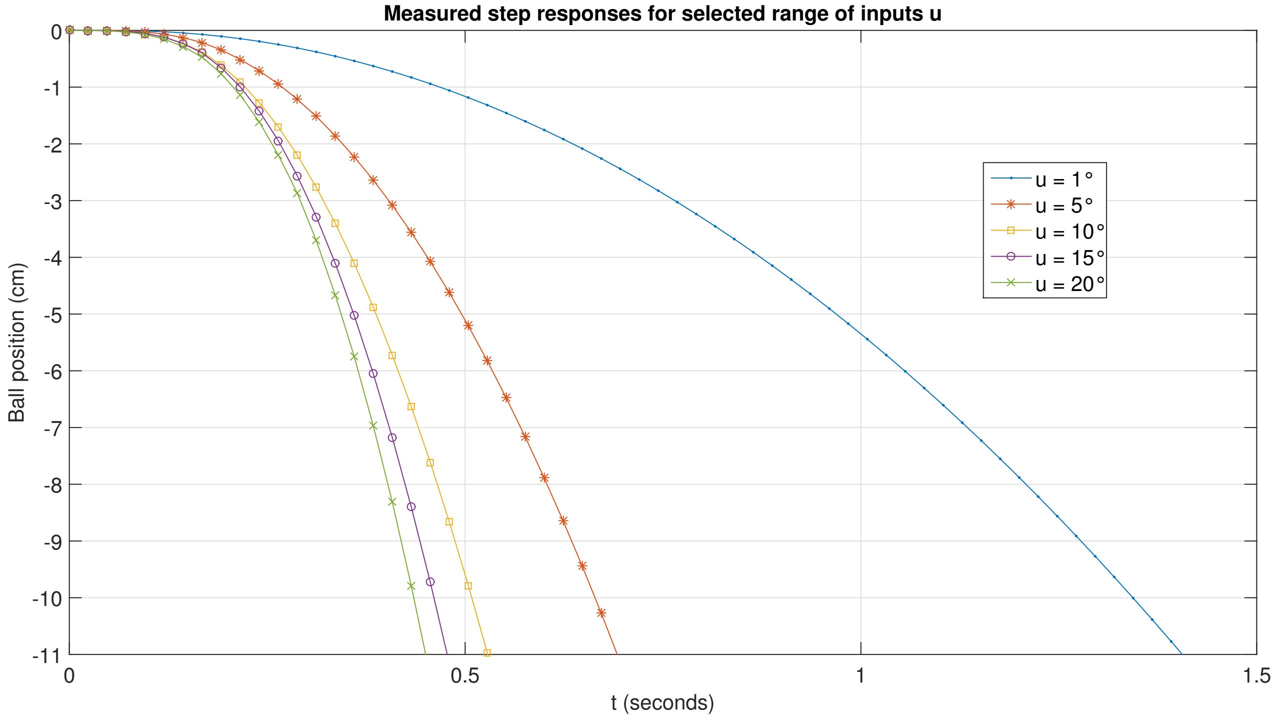

*Fig. 5.1 Pseudo-identification of the system in simulation*

These results were approximated by a least-square minimization method and

Nelder-Mead simplex algorithm to find parameters of equation (4.7) according to these measurements. These parameters for 5-degree step change are shown in (5.1) and Fig. 5.1.

$$G(s) = \frac{K}{s^2(T_r s + 1)} = \frac{-0.1306}{s^2(0.1167s + 1)} \tag{5.1}$$

### 5.1.2 Controller Parameters

A discrete version of equation (5.1) for a chosen time period of 0.05 $s$ is shown in (5.2).

$$G(z^{-1}) = \frac{(-2.101z^{-1} - 7.577z^{-2} - 1.696z^{-3})10^{-5}}{1 - 2.652z^{-1} + 2.303z^{-2} - 0.6515z^{-3}} \tag{5.2}$$

This time period was chosen in accordance with the dynamics of the manipulator. It is expected that the angle of the plate will be bound by $< -2°, 2° >$ range (higher angles have a small effect on the ball near the center of the plate and too large angles can introduce strong non-linearity to the ball movement such as jumping). Lower time period values could introduce unwanted noise readings and as shown in Fig. 5.1 it is enough considering the dynamics of the ball even for larger angles. The 2 DoF polynomial LQ controller is obtained from the characteristic polynomial of the system described in Fig. 4.2, where half of the characteristic polynomial is calculated by spectral factorization for a more optimal control strategy and the second half is selected by pole placement method with all three poles equal to $pp_{1,2,3} = 0.92$. The resulting characteristic polynomial is shown in (5.3) and used for the calculation of controller parameters. These are shown in equations (5.4) and (5.5).

$$\begin{aligned} D(z^{-1}) = 1 - 5.3008z^{-1} + 11.677z^{-2} - 13.678z^{-3} + \\ + 8.9825z^{-4} - 3.1341z^{-5} + 0.4537z^{-6} \end{aligned} \tag{5.3}$$

$$C_f(z^{-1}) = \frac{-0.007652}{1 - 1.6499z^{-1} + 0.6969z^{-2}} \tag{5.4}$$

$$C_b(z^{-1}) = \frac{-32.058 + 83.672z^{-1} - 71.644z^{-2} + 20.022z^{-3}}{1 - 1.6499z^{-1} + 0.6969z^{-2}} \tag{5.5}$$

### 5.1.3 Results

Simulation measurements were done directly in RobotStudio which provides not only full virtualization of the robot but also simulates the ball position sensor and takes care of physics simulation. Ball positions were directly connected to the robot's control system which provides also tools for the implementation of the calculated controller. This system was able to successfully control the ball on the plate and handle any external disturbances. These disturbances were simulated using RobotStudio's tool for object manipulation during simulation. Disturbances with random force and direction were introduced in the system, similar to pushing the ball in the real world. Results of this ball stabilization control are presented in Fig. 5.2 for $x$ coordinate of the ball and in Fig. 5.3 for $y$ coordinate.

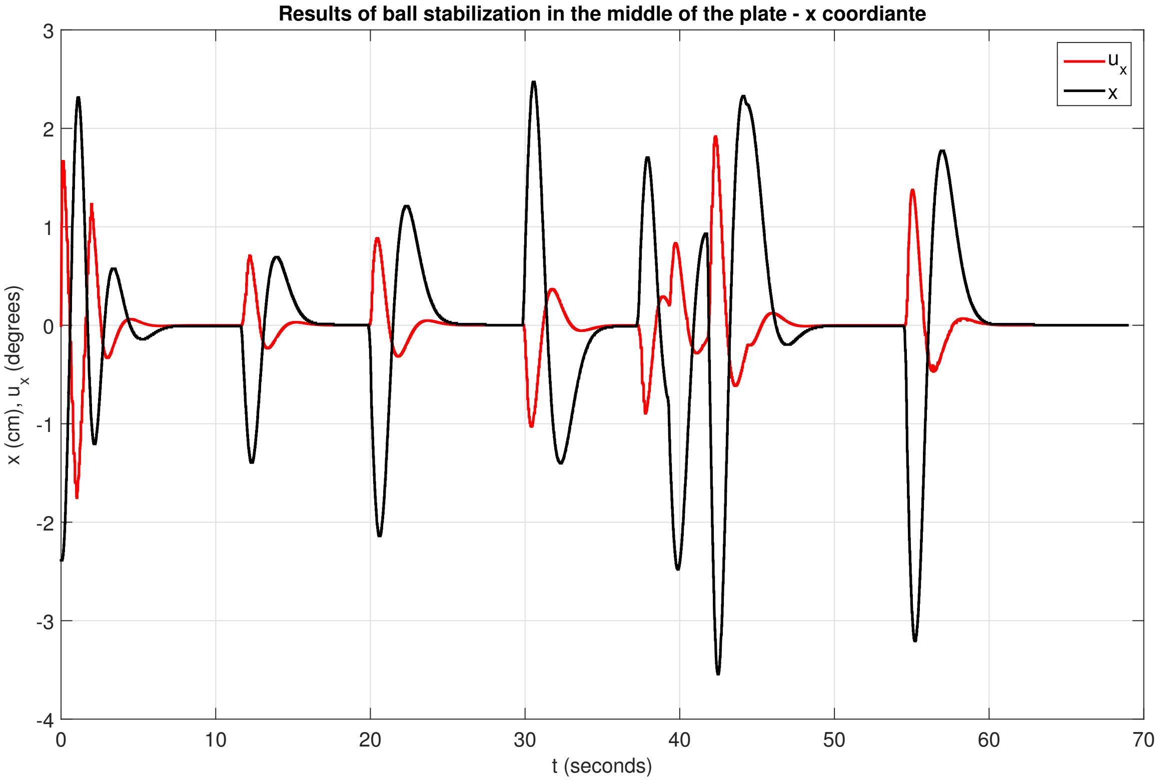

*Fig. 5.2 Simulation results for $x$ coordinate*

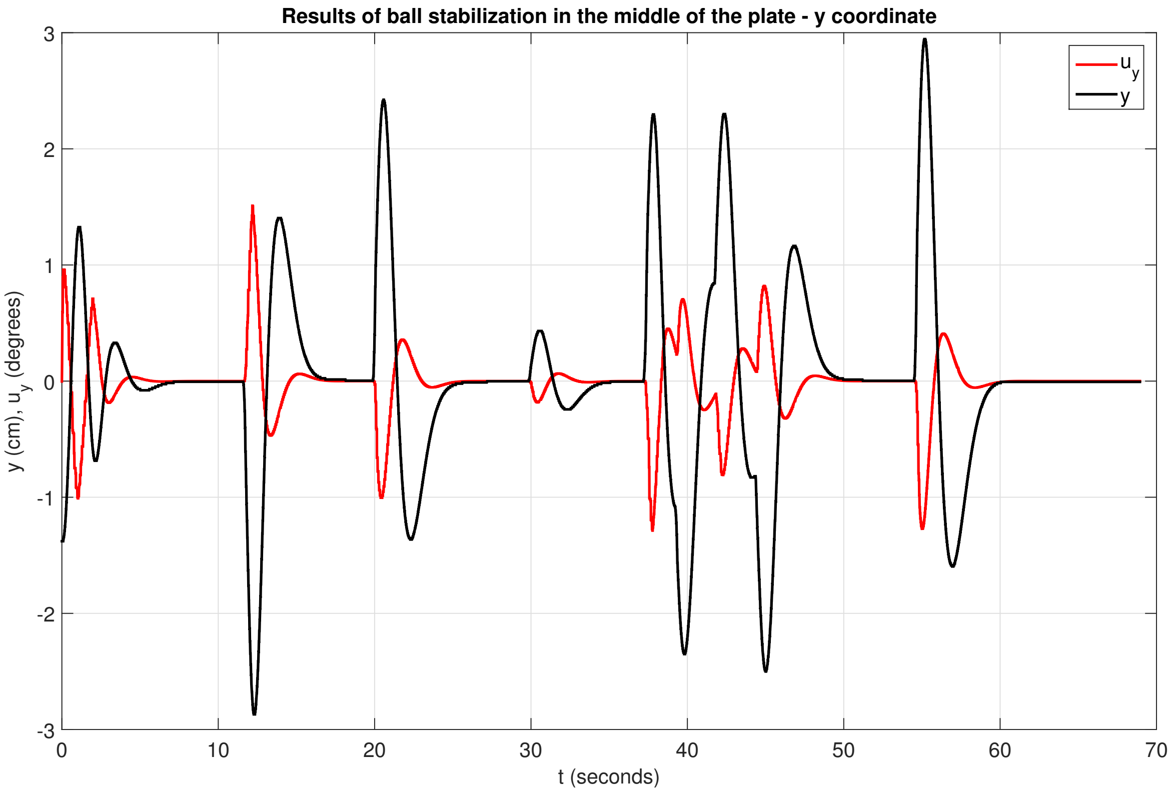

*Fig. 5.3 Simulation results for $y$ coordinate*

## 5.2 Real System

The ball & Plate system mounted on the robotic manipulator is presented in this chapter, starting with its identification and controller design. Step and harmonic signals are tested and their results are shown for both axes and also in the x-y plane. The real system is not symmetric for $x$ and $y$ coordinates and thus requires separate calculations for both coordinates, although the differences are not large and could be easily simplified to errors in the model and thus disturbances in the system.

### 5.2.1 B&P Robotic System Identification

Identification of the real system was conducted in a similar manner as for the virtual one, but multiple measurements were taken to decrease the error (Fig. 5.4 showing measurements for 2-degree step change). Each measurement was identified and the resulting coefficients of equation (4.7) were averaged to obtain a single transfer function of the system shown in equation (5.6) for the $x$ coordinate and equation (5.7) for the $y$ coordinate (they are not exactly symmetric in the real system). Response of this function is directly plotted over measurements for 2-degree step change in Fig. 5.4, but was obtained from averaged coefficients of measurements for different step changes.

$$G_x(s) = \frac{K}{s^2(T_r s + 1)} = \frac{0.8306}{s^2(0.4687s + 1)} \tag{5.6}$$

$$G_y(s) = \frac{K}{s^2(T_r s + 1)} = \frac{0.9168}{s^2(0.4108s + 1)} \tag{5.7}$$

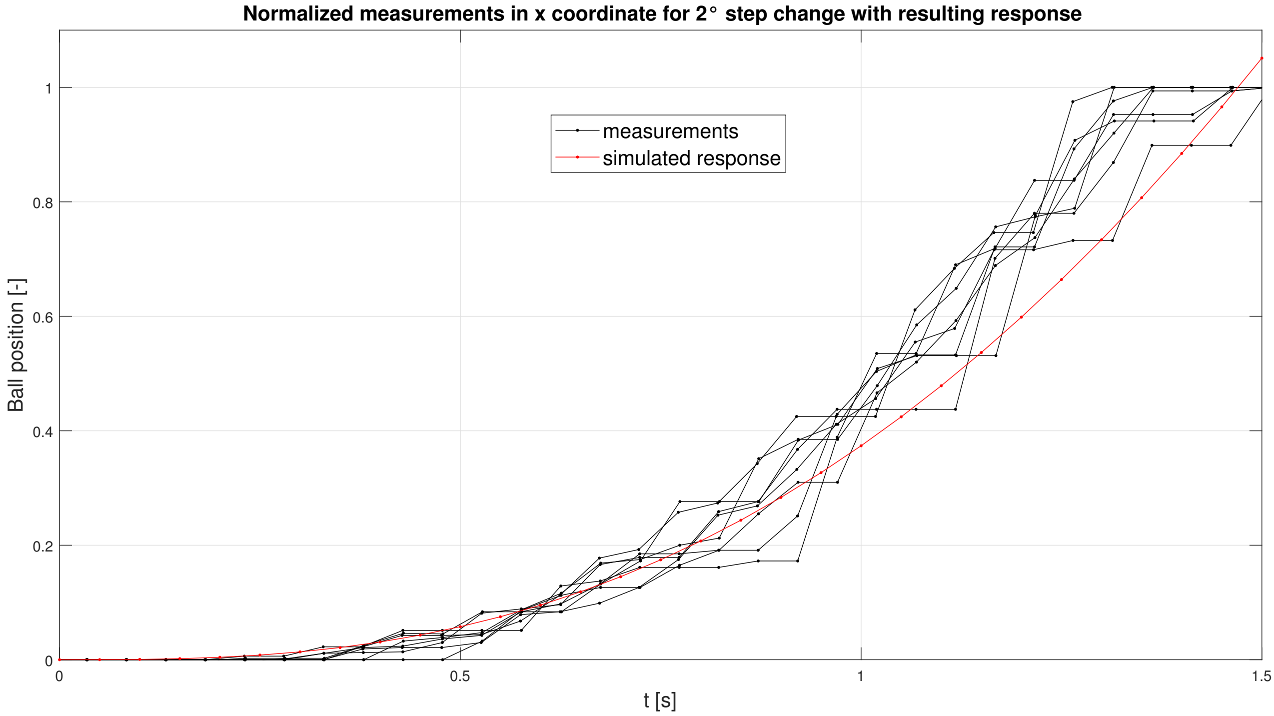

*Fig. 5.4 Measurements with the response of averaged coefficients*

### 5.2.2 Controller Parameters

Similarly to simulation chapter 5.1.2, equations (5.6), (5.7) are discretized for a time period of 0.05 $s$ and shown in (5.8) and (5.9).

$$G_x(z^{-1}) = \frac{(3.596z^{-1} + 14.01z^{-2} + 3.409z^{-3})10^{-5}}{1 - 2.899z^{-1} + 2.798z^{-2} - 0.8988z^{-3}} \tag{5.8}$$

$$G_y(z^{-1}) = \frac{(4.512z^{-1} + 17.51z^{-2} + 4.245z^{-3})10^{-5}}{1 - 2.885z^{-1} + 2.771z^{-2} - 0.8854z^{-3}} \tag{5.9}$$

The approach to controller design is the same as in chapter 5.1.2 and results are shown for both coordinates - final characteristic polynomials in (5.10) and (5.11) and resulting controllers in (5.12)-(5.15).

$$\begin{aligned} D_x(z^{-1}) = 1 - 5.5524z^{-1} + 12.847z^{-2} - 15.854z^{-3} + \\ + 11.006z^{-4} - 4.0751z^{-5} + 0.6287z^{-6} \end{aligned} \tag{5.10}$$

$$\begin{aligned} D_y(z^{-1}) = 1 - 5.5446z^{-1} + 12.810z^{-2} - 15.784z^{-3} + \\ + 10.939z^{-4} - 4.0437z^{-5} + 0.6228z^{-6} \end{aligned} \tag{5.11}$$

$$C_{f_x}(z^{-1}) = \frac{0.001462}{1 - 1.6542z^{-1} + 0.7001z^{-2}} \tag{5.12}$$

$$C_{b_x}(z^{-1}) = \frac{17.438 - 49.789z^{-1} + 47.356z^{-2} - 15.004z^{-3}}{1 - 1.6542z^{-1} + 0.7001z^{-2}} \tag{5.13}$$

$$C_{f_y}(z^{-1}) = \frac{0.000975}{1 - 1.6598z^{-1} + 0.7039z^{-2}} \tag{5.14}$$

$$C_{b_y}(z^{-1}) = \frac{12.691 - 36.115z^{-1} + 34.224z^{-2} - 10.799z^{-3}}{1 - 1.6598z^{-1} + 0.7039z^{-2}} \tag{5.15}$$

### 5.2.3 Results

Two approaches were implemented for controlling the manipulator's movement - sending angles to the robot's motion planner and bypassing the motion planner by sending desired angles directly to the motion system. All results for ball positions are normalized to compensate for unequal dimensions of the plate (322 x 247 mm) during comparisons. Both approaches are presented below for the stabilization process.

*Direct Method (using the motion planner)*

The first option is easier to implement and is a standard programming method for robotic manipulators. The robot has prepared routines for communication with its motion planner in the form of standard linear or joint motion commands. The motion planner reads these commands, interpolates the path, and plans the movement accordingly. This has a clear setback in added computation overhead and responsiveness because once the motion is planned it has to be executed which goes directly against the idea of rapidly changing values from the controller. Results of ball stabilization in the center after an initial random disturbance are shown in Fig. 5.5 and Fig. 5.6. These results show pretty poor stabilization because the motion planner is not able to keep up with the controller and introduces unexpected (and random) time delay into the system in tenths of a second.

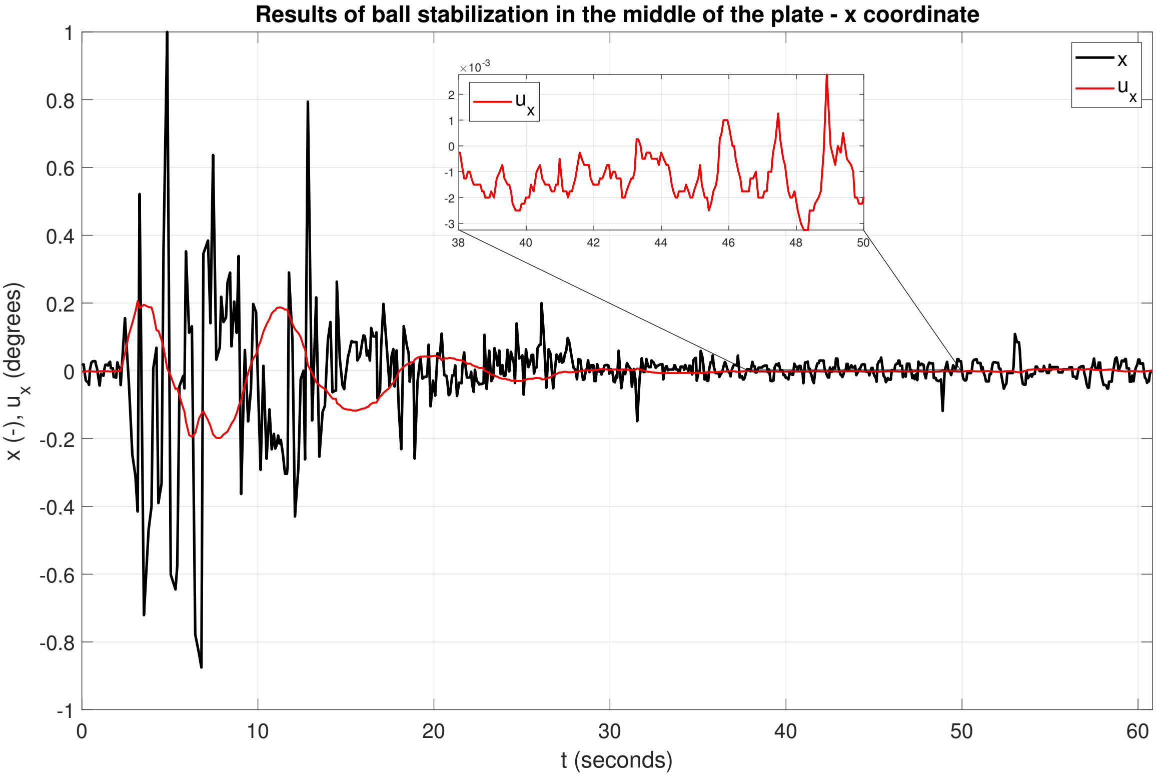

*Fig. 5.5 Control results for x coordinate with motion planner*

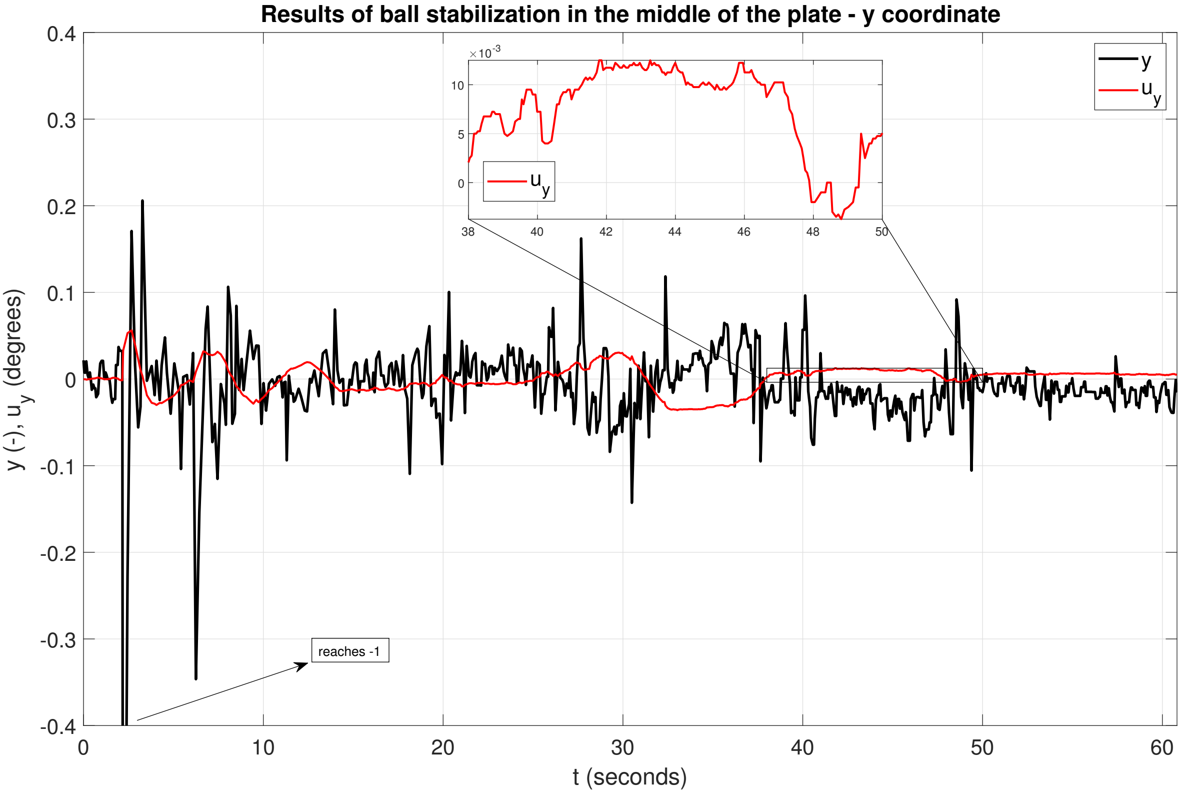

*Fig. 5.6 Control results for y coordinate with motion planner*

*Robot Guided Method (bypassing the motion planner)*

The second option is faster as it bypasses the motion planner and is also more responsive to sudden changes because it does not follow a point-to-point strategy. Results for ball stabilization can be seen in Fig. 5.7 and Fig. 5.8 for $x$ and $y$ coordinates respectively and in Fig. 5.9 which shows the position of the ball on the plate in both coordinates. Multiple disturbances were introduced in the form of random impulse force applied externally to the ball and graphs clearly show when in time was the force applied. Desired reference value was $0°$ (in the center of the plate), so the stabilization and disturbance rejection can be clearly shown.

Graphs show the controller is able to respond to disturbances and stabilize the ball in the center in 3-5 seconds depending on the magnitude of the external force applied. Magnitudes of forces (or rather the deflection of the position of the ball) can be seen in the x-y plot (Fig. 5.9) as diagonal peaks of the ball's position.

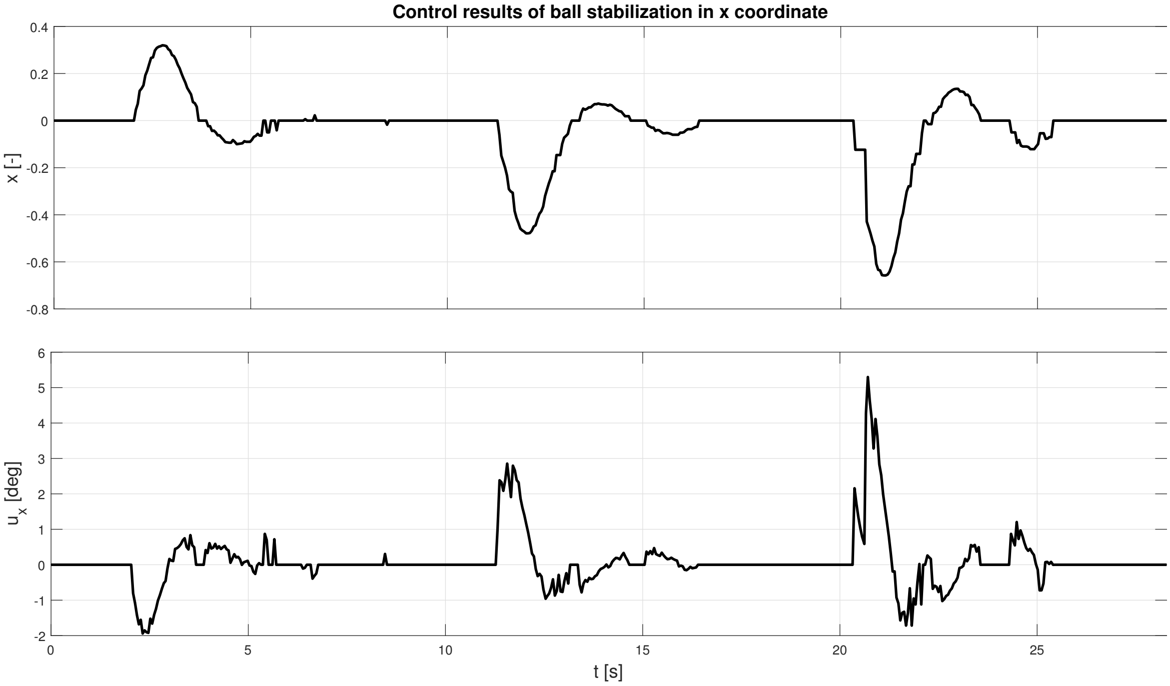

*Fig. 5.7 Control results for stabilization in x coordinate*

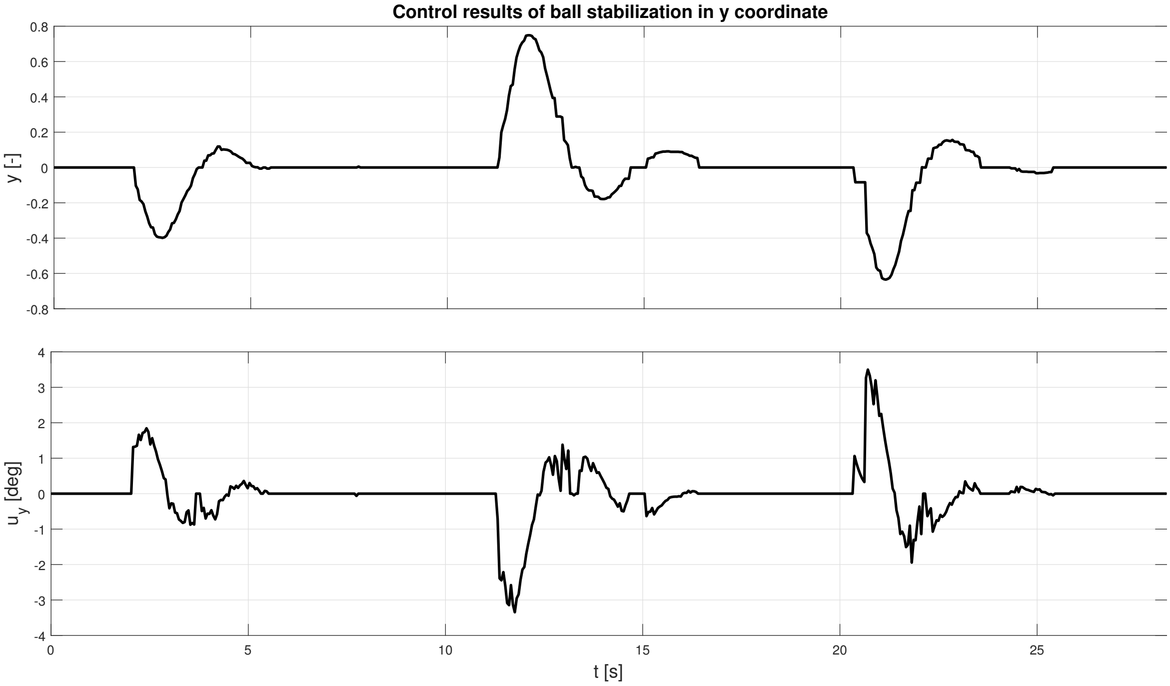

*Fig. 5.8 Control results for stabilization in y coordinate*

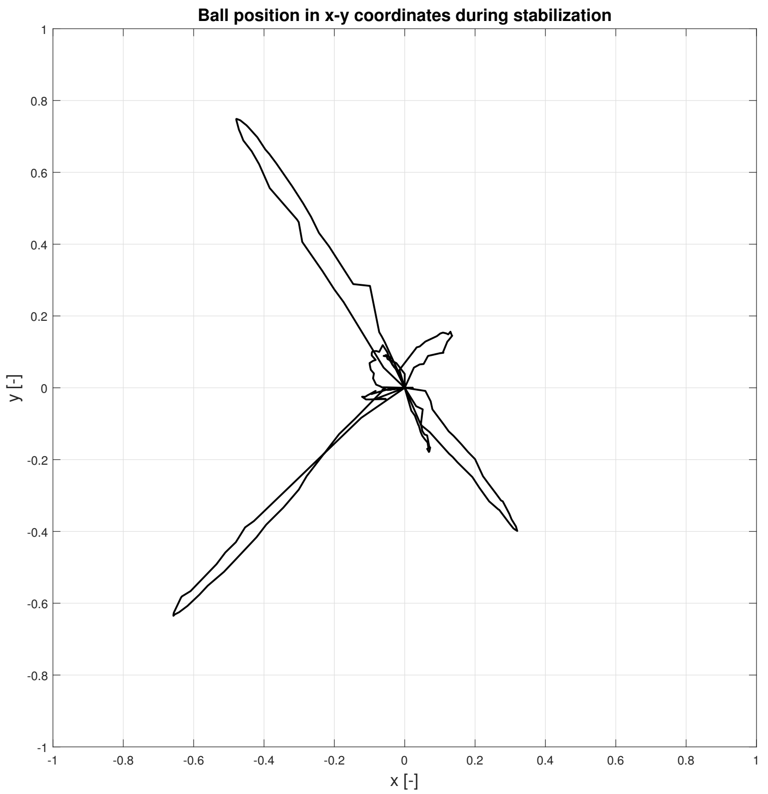

*Fig. 5.9 Control results for stabilization in x-y plane*

Another set of tests was a harmonic change of the reference value. The controller has to be designed for harmonic change reference value, which needs an additional calculation of the nominator of the feed-forward part of the controller (in equations (5.12) and (5.14)), more closely described in [15]. The controller designed for a targeted frequency of 0.25 *Hz* was thus calculated and implemented as seen in equations (5.16) and (5.17).

$$C_{f_x}(z^{-1}) = \frac{-0.07329 + 0.07198z^{-1}}{1 - 1.6542z^{-1} + 0.7001z^{-2}} \tag{5.16}$$

$$C_{f_y}(z^{-1}) = \frac{-0.06677 + 0.06608z^{-1}}{1 - 1.6598z^{-1} + 0.7039z^{-2}} \tag{5.17}$$

Results of measurements for the harmonic desired value with 0.25 *Hz* frequency are shown in Fig. 5.10-Fig. 5.12 and clearly show only a slight phase shift between reference and output values. It follows the reference value quite reliably and manages to make 8 complete revolutions in 35 seconds.

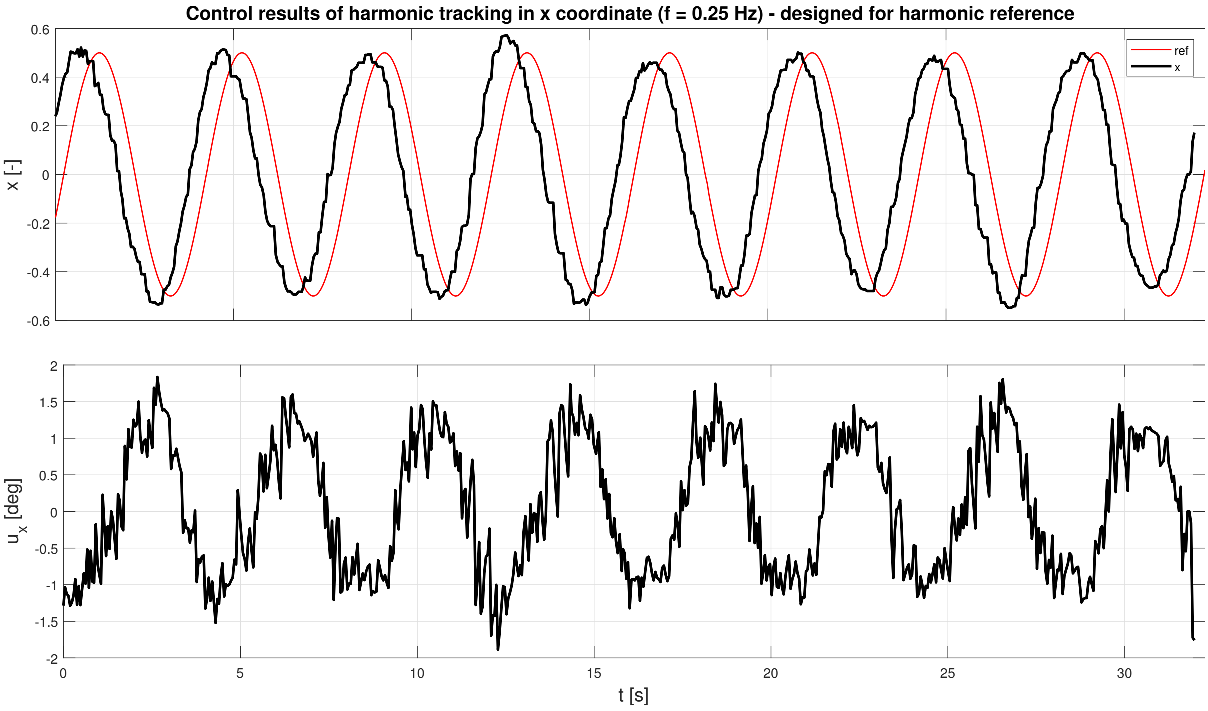

*Fig. 5.10 Control results for harmonic tracking in x coordinate*

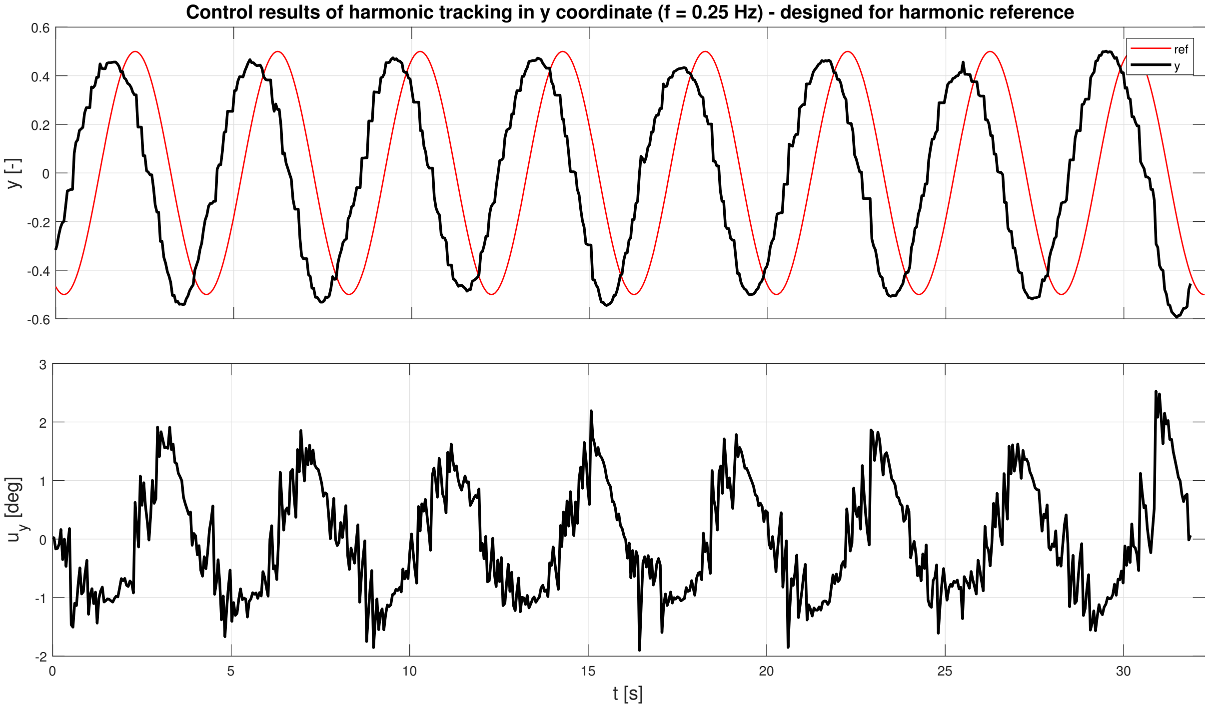

*Fig. 5.11 Control results for harmonic tracking in y coordinate*

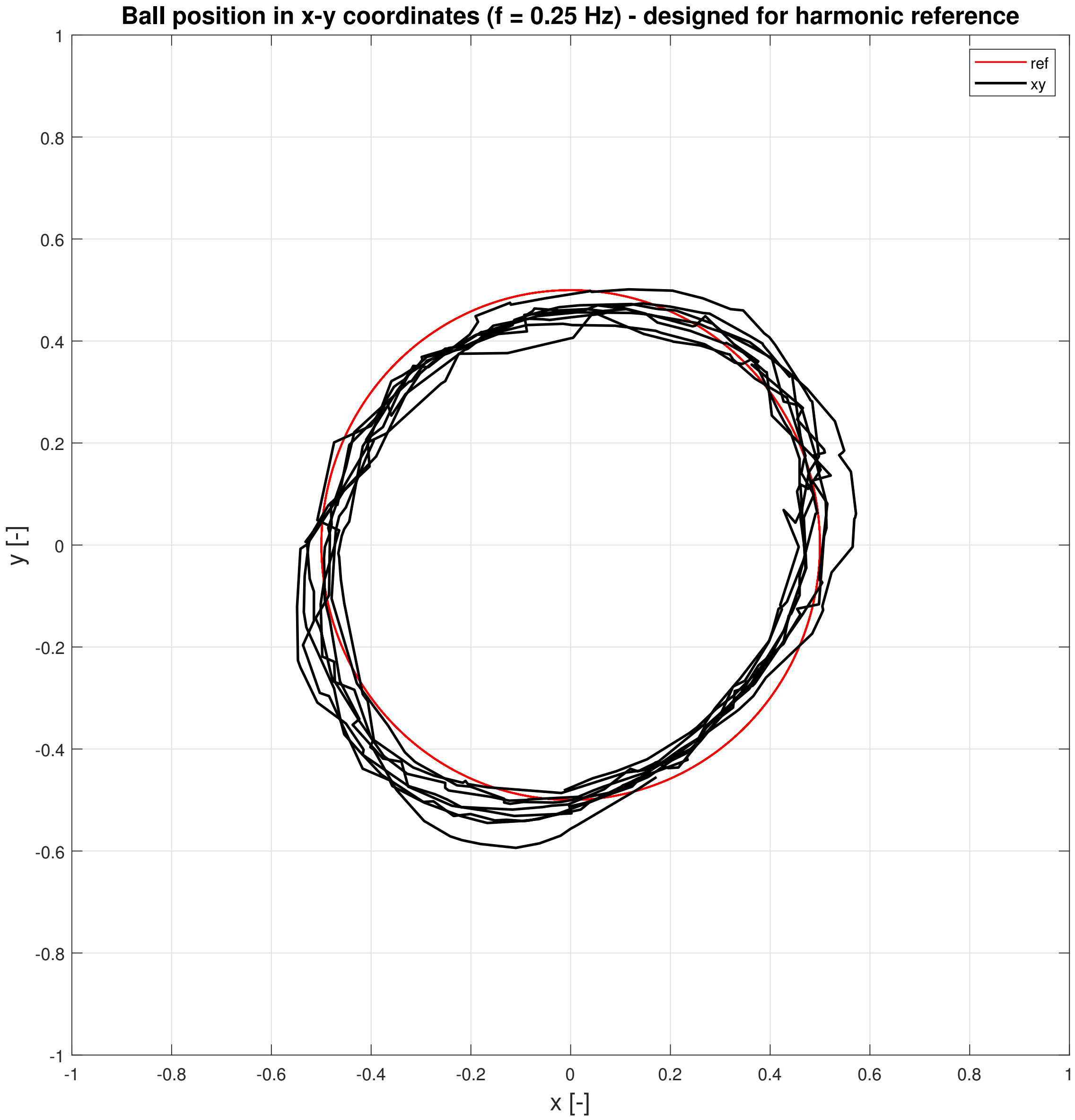

*Fig. 5.12 Control results for harmonic tracking in the x-y plane*

# 6 CONTRIBUTION TO SCIENCE AND PRACTICE

The thesis explores the topic of control of the Ball & Plate model using a robotic manipulator with 7 degrees of freedom which can be further used for educational, research, or testing purposes. A strong emphasis is put on the resulting controller effort which needs to be bound to certain limitations of robotic manipulators concerning their prolonged and repetitive use for the same task. Their transmissions and gearboxes need to withstand the control actions of the algorithm to satisfy the long operating hours needed and expected during the life cycles of these manipulators. A great advantage of using a manipulator with 7 degrees of freedom is its versatility in exploiting also translational movements of the whole plate in space. This can be achieved also by a lower degree of freedom manipulator, but the 7th axis makes it possible to choose a different configuration of the manipulator which greatly extends the kinematic flexibility of the proposed system. In addition, the introduction of errors into the system is much easier by exploiting the independent movement of one of the axes or by swiftly moving the whole plate in space. Education-oriented contribution is thus undeniable, especially in mechatronic study programs which probably already have a robotic manipulator present in their laboratories, so no other mechanical equipment is needed to have a ready-to-go Ball & Plate model. The model can be also used for testing various algorithms in different conditions and scenarios, quickly adapting to researchers' needs. Besides this it heavily relies on a real-world usage which is quite important and often over-looked aspect of many works. The practical usage and quick deployment on any type of robot available is and advantage suitable for better modularity of the whole system.

### *Peek in the Future*

The trend for the following years shows much greater automation in fields that fall out of the industrial standards because of a lack of experienced staff. Robots are going to be used for many jobs that are currently thought of as hard to automate and with the need for the supervision of a human operator. Many of these tasks in the future may require some form of control of the handled process and having a simple approach to designing a suitable controller will be a necessity. This thesis shows such a controller can be set up quickly with just a few parameters for fine-tuning to achieve a desired behavior and that the whole process can be automated quite substantially. This paves the way to no-code/low-code integrations that require as little experience and skill as possible. The deployment of these solutions will be thus much faster and leaner, and no experts in the field will be required to complete a given task. These solutions will be most probably also directly connected to AI systems, data analysis, and machine vision to better utilize the technologies available.

*Control of Unstable Systems Made Easy*

The controller design strategy presented in this thesis is showing that a (semi-optimal) 2DoF polynomial controller design approach is quite a good fit for the control of unstable systems where it can provide performance, robustness, stabilization, disturbance rejection, and trajectory tracking on par with other methods and is a worthy competitor among the vast options of different controller design strategies found in the literature. It is able to easily stabilize the process without a deep knowledge of the system which is more than suitable for quick deployment. Designing a controller for fast unstable systems is a challenge because the testing without a properly designed controller results in very unstable behavior of controlled variables and unpredictable behavior of the actuation system. The controller thus needs to be able to stabilize the system before the quality of the control can be improved and fine-tuned on the real device. The controller described in this thesis can robustly stabilize the controlled plant making any fine-tuning of its parameters quicker and more user-friendly.

*Service Life of Motion Systems During Control*

Another limitation is the service life of the robot's components while controlling a fast unstable process. Fast processes are directly linked to fast actuation and although industrial robots are designed for continuous operation with a relatively large mean time to failure, they are still prone to rapid (and unpredictable) changes in their movements. This can cause a lot of issues during their operation while controlling fast unstable systems, mainly damage to their gearboxes, servos and other mechanical parts. This thesis showed that the designed controller is able to stabilize the system relatively quickly, but with really low controller effort (especially for quick step-changes). There is always some compromise needed between quality, speed, reliability, robustness, and effort of the control and controller approach described in this thesis finds the optimal equilibrium between them. This feature, combined with ease of integration of the design, proves this is a competitive way on how to approach the problem of service life in these applications and paves the way for their usage in real life.

*An Example*

Bipedal locomotion is an unstable system and many robotic applications are aimed at this topic. It was proved that algorithms used in this thesis are more than able to stabilize the unstable system while keeping the load on actuators as low as possible and still maintaining comparable results as more standard forms of control. The algorithm calculates a semi-optimal solution to the problem, dealing with the unstable part and leaving fewer parameters to set, which are easily manageable and their effect on the whole system is more predictable in certain cases. The robustness of the proposed algorithms was not the main goal of this thesis, but it was shown that the controller can offer solid stabilization even with delayed and noisy communication between controller and actuator, although with much worse quality. All these criteria are important in real-world applications for continuous operation over multiple hours without failure and malfunctions. Algorithms proposed in this thesis can be easily made adaptive offering even more value.

# 7 CONCLUSION

This thesis discussed the theoretical context of the Ball & Plate problem and its solution utilizing a collaborative robotic manipulator as the electromechanical component of the model. It also described the design and utilization of a 2 DoF LQ polynomial controller for the specified problem and compared it in simulation with typical controller types implemented in B&P problems. The spectral factorization of polynomials was investigated in order to find a more optimal solution, compensating for the dynamics of the controlled system while maintaining the controller effort (and its rapid change) within the constraints of the manipulator. Before the experimental part was tested on the real manipulator, it was constructed in a simulation environment to check the proposed methods and approaches. Education in automation courses largely motivated by robots and industrial robotic manipulators can benefit from the findings. The path to the result extends through several disciplines and displays not only controller design ideas, but also controller-robot operation and communication, kinematics and dynamics of the robot, and the real application of the problem with its specific limits.

Ball & Plate model application on a collaborative 7-axis manipulator is not the optimal solution to this problem, but the B&P model is the best example of such a system that can be employed in laboratory conditions (together with inverted pendulum). Applications of bipedal robots can benefit tremendously from the methods suggested in this thesis, as these robots must navigate space while stabilizing their own bodies, battery packs, and, most crucially, random external forces acting on them. These applications have existed for a number of decades, but the movement of bipedal robots relied mostly on shifting the weight from one leg to another, thereby significantly lowering the instability of the movement itself. The strain on the actuators, gears, and other mechanical parts of these robots deployed in real-world applications is another crucial characteristic. Numerous controllers fail to maintain the optimal balance between rapid stabilization and low controller effort. In addition, reduced controller effort reduces the power consumption of the entire system, hence cutting operating expenses and extending the battery life of robots that require them. Thus, the results presented in this thesis conform to the outlined criteria and reliably compete with established control theory methods.

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|---|---|---|---|---|
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# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| B&P | Ball & Plate |
| cobot | Collaborative Robot |
| DoF | Degrees of Freedom |
| EGM | Externally Guided Motion |
| HW | Hardware |
| IO | Input-Output |
| LQ | Linear Quadratic |
| LQR | Linear Quadratic Regulator |
| MIMO | Multiple-Input, Multiple-Output |
| PD | Proportional-Derivative (controller) |
| PID | Proportional-Integral-Derivative (controller) |
| TCP | Tool Center Point (do not confuse with TCP Protocol) |
| UDP | User Datagram Protocol |

Ing. Ľuboš Spaček, Ph.D.

# Robotické systémy pro rychlé a nestabilní procesy

Robotic Systems in Fast and Unstable Processes

Doctoral Thesis Summary

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