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# Modeling and Control of the Ball and Beam Process

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<i>Title and subtitle</i> Modeling and Control of the Ball and Beam Process (Modellering, simulering och reglering av kula på bom processen).			
<i>Abstract</i> One of the most difficult problems that an engineer who works with modeling deals with, is the question about how to translate a physical phenomenon into a set of equations. It is usually difficult to capture all dynamics and phenomena, so one usually strives for a set of equations that describes the physical system approximately and adequately with the accuracy for the purpose. In our case, we model the dynamics relevant for control design. The topic of this thesis was to do an in-depth study of the Ball and Beam process. Two different experimental implementation of the Ball and Beam process have been considered, both available at the course lab at the Department of Automatic Control, Lund. The first step consisted of deriving the equations of motion, that is, to do the mathematical modeling of the process. In order to implement this model Modelica has been used. Modelica, which is a powerful language for modeling of physical systems, uses the tool Dymola. Another model was designed also with Modelica but with the help of the extension of the multi body library, which uses a methodology based on object orientation and symbolic manipulation of equations. With this last model it was possible to visualize an animation in real time 3D. The following step of the project was to do control design for the different models. The obtained simulations were shown in Dymola and Simulink. Finally experiments on the real process were developed, based on vision feedback.			
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# Chapter 1

## Introduction

This thesis concentrates on the study of the Ball and Beam process. The modeling has been done with Modelica and Dymola.

Dymola is an integrated environment for developing models in the Modelica language and a simulation environment for performing experiments.

To do the control design there are many possibilities; this project presents an observer-based control design development in Matlab based on pole-placement. The simulations are made in Simulink and Dymola. The experiments with the real Ball and Beam process are done with the controller implemented in a real-time extension to Simulink and visual feedback from a camera system.

A short description of the thesis chapter is outlined below:

**Chapter 2** presents an explanation of different tools used for the modeling.

**Chapter 3** describes the study of the Ball and Beam process.

**Chapter 4** presents the mathematical modeling of the physical system.

**Chapter 5** gives the modeling in Modelica of the beam and ball process.

**Chapter 6** contains control design of the obtained models and the corresponding simulations.

**Chapter 7** contains the experiments done.

**Chapter 8** presents the summarized conclusions of this thesis.

## **Chapter 2**

### **Dymola and Modelica**

This chapter gives a short introduction to the different tools used for the modeling in the thesis.

#### **2.1 Dymola**

The company Dynasim's mission is to develop the software tools that industry needs for solving demanding modeling, simulation and design problems. The emphasis is on handling large, multi-engineering systems efficiently. Dymola pioneered the object-oriented physical modeling methodology and the accompanying simulation technology.

In 1996, Dynasim took the initiative to design a new unified object-oriented language for physical systems modeling, called Modelica. Founded in 1992, Dynasim is the leading developer and implement of object-oriented multi-engineering modeling technology and the Modelica language [2].

Dymola - Dynamic Modeling Laboratory - is a tool for multi-domain modeling and simulation. Dynasim developed it. Dymola supports the modeling language Modelica for which, there are a number of free and commercial model libraries that include models of mechanical, thermal, hydraulic, and thermodynamic and control systems. [4]

Dymola uses a new modeling methodology based on object orientation and symbolic manipulation of equations. The usual need for the manual conversion of equations to a block diagram is removed by the use of automatic formula manipulation.

### 2.1.1 Dymola features:

- Model Translator
  - Automatic causality analysis
  - Symbolic solution of equations and index reduction
  - Solution of algebraic loops
  - Automatic handling of time and state events
  - Generate C-code
- Handles large, complex multi-domain models
- Faster modeling by graphical model composition
  - Graphical model editor and browser
  - Drag submodels from libraries
  - Parameter forms
  - Connect graphically
  - Build icons - polygons, circles, text, color etc...
  - Text editor for declarations and equations
  - Automatic HTML model documentation
- No manual equation manipulation needed
- Faster simulation - symbolic pre-processing
- Open for user defined model components
- Open interface to other programs
- Animation
  - Real time 3D animation
  - Boxes, spheres, cylinders, etc - predefined visual classes
  - Import of DXF and STL files
  - Hidden surface removal, shading
  - Plotting
- Simulator
  - Handles ODE and DAE models
  - State of the art numerical integration
  - Flexible initialization
  - Interface to external C-functions
  - Matlab/Simulink, xPC and SPACE interfaces
  - DDE interface
  - Real time simulation [1]

### 2.1.2 The modeling environment

Dymola is an integrated environment for developing models in the Modelica language and a simulation environment for performing experiments.

The Dymola modeling environment is divided in two main parts:

- At the modeling mode called, Model Editor, where the models are composed from library components (from the Modelica standard library, other libraries, and commercial and proprietary libraries) as well as models developed by the user. Models are either composed of other, more primitive, components, or described by equations at the lowest level.

This mode allows:

- Model composition
  - Default parameter settings
  - Definition of equations
- At the simulation mode, Dymola transforms a declarative, equation based, model description into efficient code. In this level it is possible show the results as animations or using plot windows for visualization of simulation results.

Dymola provides a complete simulation environment, but can also export code for simulation in Simulink. In addition to the usual offline simulation, Dymola can generate code for specialized hardware-in-loop systems, such as, dSPACE, xPC and others [5].

Dymola uses Modelica, which is an object orientated modeling language, which supports hierarchical structuring, reuse and evolution of large and complex models independent from the application. It uses acausal modeling based on differential and algebraic equations.

## 2.2 Modelica

Modelica [3] is a powerful language for modeling of physical systems designed to support effective library development and model exchange. It is a modern language built on acausal modeling with mathematical equations and object-oriented constructs to facilitate reuse of modeling knowledge.

The work with Modelica started in September 1996 with a group of about fifteen persons with knowledge about modeling languages and models with differential algebraic equations (DAE).

The first version of the Modelica language definition was finished in September 1997. In January 2002 a new version was released.

### 2.2.1 Modelica features

The four most important features of Modelica are:

- Is based on equations instead of assignment statements. This permits acausal modeling that gives better reuse of classes since equations do not specify a certain data flow direction. Thus a Modelica class can adapt to more than one data flow context.
- Has multi-domain capability, meaning that model components corresponding to physical objects from several different domains such as e.g. electrical, mechanical, thermodynamic, hydraulic, biological and control applications can be described and connected.
- Is an object-oriented language with a general class concept that unifies classes, generics, and general subtyping into a single language construct. This facilitates reuse of components and evolution of models.
- Has a strong software component model, with constructs for creating and connecting components. Thus the language is ideally suited as an architectural description language for complex physical systems, and to some extent for software systems.

Models and sub-models are declared as classes with connection interfaces called *connectors*. This connection capability allows the use of model libraries to compose complex models with the drag and drop and connection drawing facilities of modern graphical editors.

The goal of the Modelica design effort is to design physical systems modeling language that makes life for the model builders considerably easier and more productive.

Following are described the general features of Modelica.

#### **Hierarchical modeling**

Modelica supports both high levels modeling by composition and detailed library component modeling by equations. Models of standard components are typically available in model libraries. Using a graphical model editor, a model can be defined by drawing a composition diagram by positioning icons that represent the models of the components, drawing connections and giving parameter values in dialogue boxes. Constructs for including graphical annotations in Modelica make icons and composition diagrams portable between different tools [2].

An example of the textual representation of a simple motor drive system is:

```

model MotorDrive
  PID      controller:
  Motor    motor;
  Gearbox  gear (n=100);
  Inertia  inertia (J=10);
equation
  connect(controller.outPort, motor.inPort);
  connect(controller.inPort2, motor.outPort);
  connect(gear.flange_a, motor.flange_b);
  connect(gear.flange_b, inertia.flange_a);
end MotorDrive;

```

The composition diagram of the model class Motor is shown below:

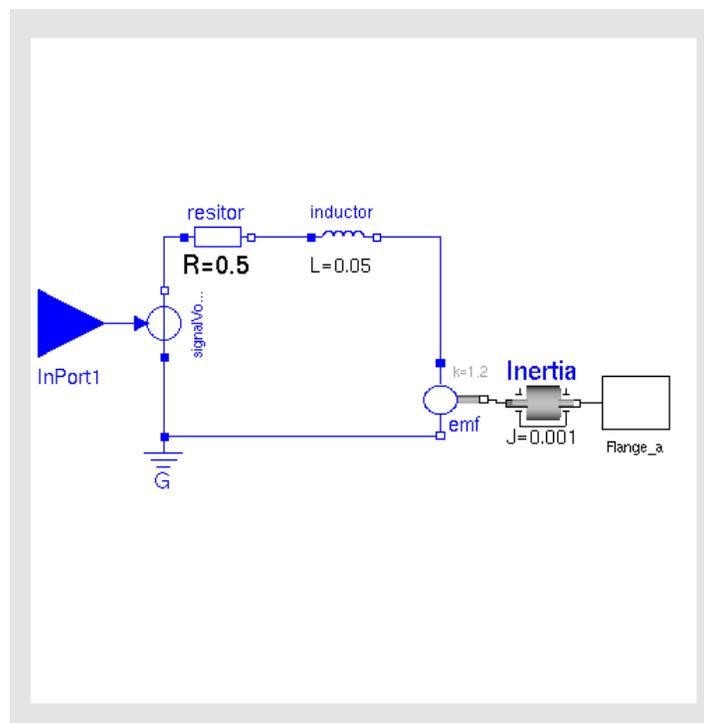


Figure 2.1: Motor drive with Modelica libraries

### **Structure model libraries**

A powerful package concept is available to structure large model libraries and to find a component in a file system giving its hierarchical Modelica class name.

### **Hybrid modeling**

A unique feature of Modelica is the handling of discontinuous and variable structure components such as relays, switches, bearing friction, clutches, brakes, impact, sampled data systems, automatic gearboxes etc. Modelica has introduced special language constructs allowing a simulator to introduce efficient handling of events needed in such cases.

### **Array**

Modelica supports arrays, utilizing a Matlab like syntax. The elements of arrays may be of the basic data types (Real, Integer, Boolean, String) or component models. This allows convenient discretization of simple partial differential equations.

### **Class parameters**

Besides ordinary numeric parameters, Modelica allows model class parameters. As an example assume that an auto-tuning controller should replace a PI controller. It is of course possible to just replace the controller in a graphical user environment, i.e., to create a new model. The problem with this solution is that two models must be maintained. Modelica has the capability to instead substitute a model component so only one version of the rest of the model is needed.

### **Equations**

Models in Modelica are mathematically described by differential, algebraic and discrete equations. No particular variable needs to be solved manually. A Modelica tool will have enough information to decide it automatically. Modelica is designed such that available, specialized algorithms can be utilized to enable efficient handling of large models having more than hundred thousand equations. Modelica is suited and used for hardware-in-the-loop simulations and for embedded control systems.

### 2.3 How to learn Dymola and Modelica

The first task of this thesis was learning Dymola and the Modelica language. In my computer version (5.1) of Dymola was installed, available as free source code. Most of the existing tutorials are based on examples, besides I used several tutorials and books, some of them were:

- The guide “Getting Started with Dymola” [1] included in Dymola user’s manual which provides some examples in order to guide you through Dymola. For detailed information about the program, you can consult the on-line documentation available in the Help menu, after selecting Documentation.
- The book “Introduction to Physical Modeling with Modelica” [6], which introduces to the Modelica modeling language and shows the use the powerful features of the Modelica language.
- A tutorial package called “Beginner tutorial” [7], which contains exercises. These exercises are good to learn to write simple models, the use the Modelica standard library etc...
- *Modelica tutorial document* and *Modelica specification document*, both define the Modelica language [8].
- *Advanced Tutorial* is a continuation of Beginner tutorial [9].

## Chapter 3

### Ball and Beam

This chapter gives an introduction to the process of the ball rolling on the beam.

#### 3.1 Process Description

The ball and beam system is one of the most enduringly popular and important laboratory models for teaching control systems engineering. The ball and beam is widely used because it is very simple to understand as a system, and yet the control techniques that can be studied it cover many important classical and modern design methods. It has a very important property; it is open loop unstable.

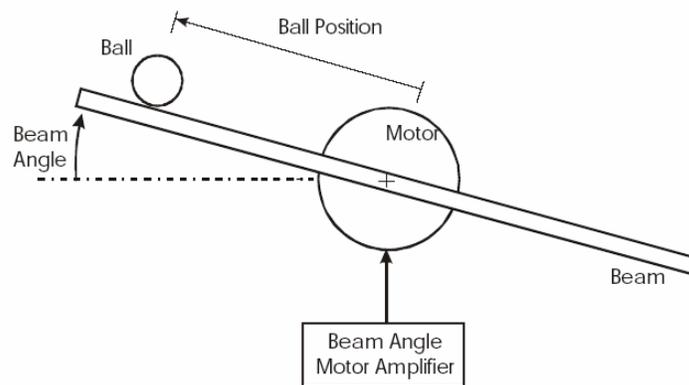


Figure 3.1: Diagram of Ball and Beam

The system is very simple, a steel ball rolling on the top of a long beam. The beam is mounted on the output shaft of an electrical motor and so the beam can be tilted about its center axis by applying an electrical control signal to the motor amplifier.

The control job is to automatically regulate the position of the ball on the beam by changing the angle of the beam. This is a difficult control task because the ball does not stay in one place on the beam but moves with acceleration that is approximately proportional to the tilt of the beam. In control terminology the system is open loop unstable because the system output (the ball position) increases without limit for a fixed input (beam angle). Feedback control must be used to stabilize the system and to keep the ball in a desired position on the beam.

Two different implementations of the Ball and Beam process have been considered, both available at the course lab of the Department of Automatic Control, see figure 3.2 and 3.3.

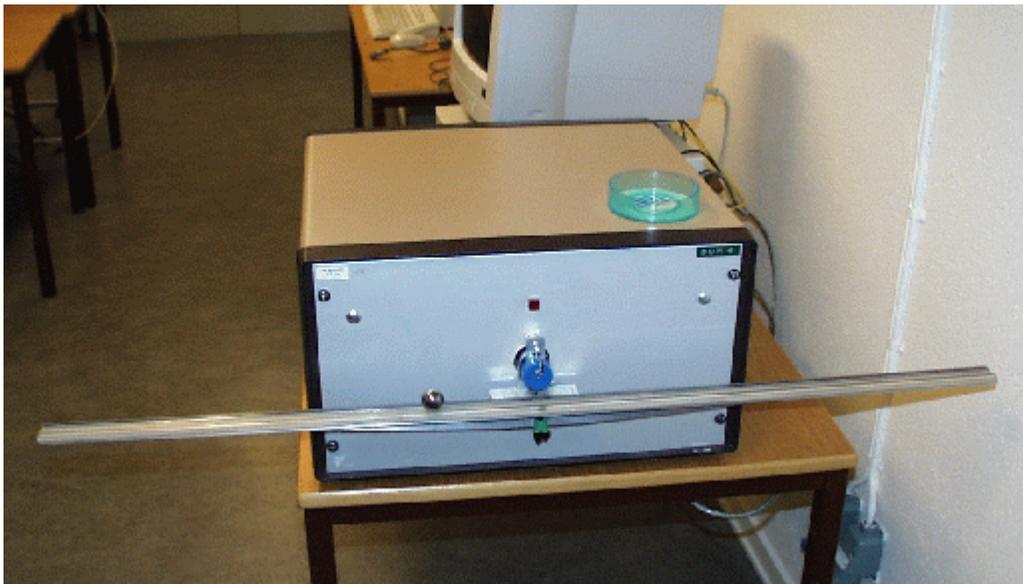


Figure 3.2: Ball and Beam connected via gearbox

The beam is connected to a velocity controlled DC-motor via a gearbox. This makes it much easier to control the process and there is very little influence of the cross-couplings from the ball to the beam.



Figure 3.3: Ball and Beam directly connected to the axis of a DC-motor

Direct driven beam: The beam is directly connected to the axis of a DC-motor.

The beam angle is measured but not the angular velocity. The ball position needs also to be measured and in the standard configuration of the process at the Department of Automatic Control the metal ball closes an electrical circuit along the rail of the beam.

In our experimental setup, see chapter 7, we have used a vision system for determining the ball position. The speed of the ball needs to be estimated.

## Chapter 4

### Mathematical modeling

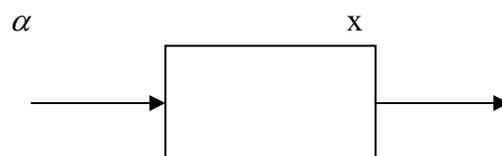
This chapter describes how to obtain the equations of motion for the Ball and Beam process.

#### 4.1 Ball and Beam Model

The equations for obtaining the model in Modelica have been realized by means of two different methods. One of them is derived with simple mathematic equations using Newton's second law and another through the use of the Lagrangian Method.

##### 4.1.1 Newton's second law

In this model we first consider only the relation between the beam angle and the position of the ball.



The parameters of the ball and beam are defined as follows:

- $\alpha$  → Beam angle coordinate
- $L$  → Beam Length
- $m$  → Mass of the ball
- $R$  → Radius of the ball
- $J$  → Ball's moment of inertia
- $G$  → Gravitational acceleration
- $x$  → Position of the ball

Neglecting frictional forces, the two forces influencing the motion of the ball are:

- $F_{tx}$  Force due to translational motion
- $F_{rx}$  Force due to ball rotation

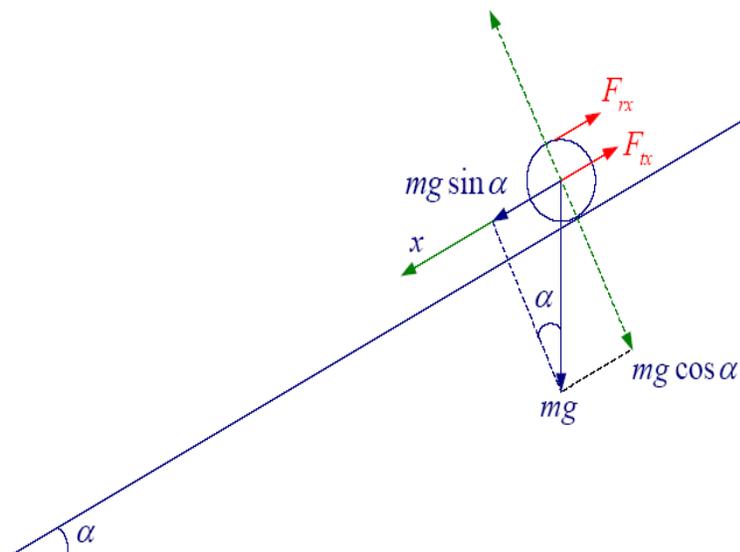
Translational:

$$\ddot{x} = \frac{d^2x}{dt^2} \quad F_{tx} = m \cdot \ddot{x} \quad (4.1)$$

Torque due to the ball rotation is:

$$T_r = F_{rx} \cdot R = J \cdot \frac{d\omega_b}{dt} = J \cdot \frac{d\left(\frac{v_b}{R}\right)}{dt} = J \cdot \frac{d^2\left(\frac{x}{R}\right)}{dt^2} = \frac{J}{R} \cdot \ddot{x}$$

$$F_{rx} = \frac{J}{R^2} \cdot \ddot{x} \quad (4.2)$$



The moment inertia of the ball is (sphere):

$$J = \frac{2}{5} \cdot m \cdot R^2 \quad (4.3)$$

Substituting the equation (4.3) into the equation (4.2), we get:

$$F_{rx} = \frac{2}{5} \cdot m \cdot \ddot{x}$$

Newton's second law along the inclination:

$$F_{rx} + F_{ix} = m \cdot g \cdot \sin \alpha \quad (4.4)$$

Substituting in the equation (4.4):

$$\frac{2}{5} \cdot m \cdot \ddot{x} + m \cdot \ddot{x} = m \cdot g \cdot \sin \alpha$$

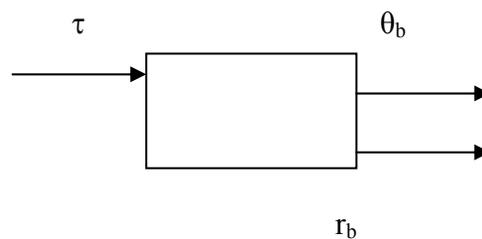
In conclusion, we have:

$$\ddot{x} = \frac{5}{7} \cdot g \cdot \sin \alpha$$

In this derivation we have taken into consideration how the ball position affects the angle  $\alpha$ .

### 4.1.2 Lagrangian methods

The control objective is to control the torque  $\tau$  applied at the pivot of the beam, such that the ball can roll on the beam and track a desired trajectory. The torque causes thus a change of the beam angle and a movement in the position of the ball.



The parameters of the ball and beam are defined as follows:

- $I_b \rightarrow$  Beam's moment of inertia
- $\theta_b \rightarrow$  Beam angle
- $m_s \rightarrow$  Mass of the ball
- $I_s \rightarrow$  Ball's moment of inertia
- $r_s \rightarrow$  Radius of the sphere
- $r_b \rightarrow$  Position of the ball

The kinetic energy of the system is:

$$T = T_{beam} + T_{sphere}$$

$$T_{beam} = (T_{beam})_{frame} + (T_{beam})_{beam\_body\_center}$$

$$T_{sphere} = (T_{sphere})_{frame} + (T_{sphere})_{beam\_body\_center}$$

Each energy is:

$$(T_{beam})_{frame} = 0$$

➤ The rotational kinetic energy of the beam is:

$$T_{beam,center} = \frac{1}{2} \cdot I_b \cdot \dot{\theta}_b^2$$

➤ The ball has kinetic energy with respect to the frame in both radial and circular motion:

$$T_{sphere,frame} = \frac{1}{2} \cdot (m_s \cdot r_b^2) \cdot \dot{\theta}_b^2 + \frac{1}{2} \cdot m_s \cdot \dot{r}_b^2$$

➤ The rotational kinetic energy of the sphere about its body center,

$$T_{sphere,center} = \frac{1}{2} \cdot I_s \cdot \dot{\theta}_s^2 \quad (4.5)$$

The rotational inertia of the rolling sphere is

$$I_s = \frac{2}{5} \cdot (m_s \cdot r_s^2) \quad (4.6)$$

and applying a rolling without slipping:

$$\dot{r}_b = r_s \cdot \dot{\theta}_s \quad (4.7)$$

Substituting the equations (4.6) and (4.7) into the equation (4.5), we get:

$$T_{\text{sphere,center}} = \frac{1}{2} \cdot \left[ \frac{2}{5} \cdot (m_s \cdot r_b^2) \right] \cdot \left[ \frac{1}{r_s^2} \cdot \dot{r}_b^2 \right] = \frac{1}{2} \left[ \frac{2}{5} \cdot m_s \cdot \dot{r}_b^2 \right]$$

The kinetic energy of the system is:

$$T = \frac{1}{2} \cdot \left[ I_b \cdot \dot{\theta}_b^2 + (m_s \cdot r_b^2) \cdot \dot{\theta}_b^2 + m_s \cdot \dot{r}_b^2 + \frac{2}{5} \cdot m_s \cdot \dot{r}_b^2 \right] \quad (4.8)$$

Simplifying the equation (4.8), we have:

$$T = \frac{1}{2} \cdot \left[ (I_b + m_s \cdot r_b^2) \cdot \dot{\theta}_b^2 + \frac{7}{5} \cdot m_s \cdot \dot{r}_b^2 \right]$$

The rolling ball alone exhibits the potential energy of the system:

$$V = m_s \cdot g \cdot r_b \cdot \sin \theta_b$$

To sum up:

➤ **KINETIC ENERGY**

$$T = \frac{1}{2} \cdot \left[ (I_b + m_s \cdot r_b^2) \cdot \dot{\theta}_b^2 + \frac{7}{5} \cdot m_s \cdot \dot{r}_b^2 \right] \quad (4.9)$$

➤ **POTENTIAL ENERGY**

$$V = m_s \cdot g \cdot r_b \cdot \sin \theta_b \quad (4.10)$$

To write the equations of motion, we define the Lagrangian  $L$ , to be the difference between the kinetic and potential energy of the system.

$$L(q, \dot{q}) = T(q, \dot{q}) - V(q) \quad (4.11)$$

where  $q$  denote the so-called generalized coordinates of the system,  $T$  is the kinetic energy of the system and  $V$  is the potential energy of the system.

Substituting the equations (4.9) and (4.10) into the equation (4.11), we get:

$$L = \frac{1}{2} \cdot \left[ I_b \cdot \dot{\theta}_b^2 + (m_s \cdot r_b^2) \cdot \dot{\theta}_b^2 + m_s \cdot \dot{r}_b^2 + \frac{2}{5} \cdot m_s \cdot \dot{r}_b^2 \right] - m_s \cdot g \cdot r_b \cdot \sin \theta_b$$

Lagrange's equations of motion are formed from:

$$\frac{d}{dt} \left[ \frac{\partial L}{\partial \dot{q}_i} \right] - \frac{\partial L}{\partial q_i} = F_{q_i}$$

where  $F_{q_i}$  is the external force, in this case  $F_{q_i}$  is  $\tau$ .

$q_i \rightarrow$  in this case are  $\theta_b$  and  $r_b$

$$\frac{\partial L}{\partial \dot{\theta}_b} = \frac{1}{2} \cdot (I_b + m_s \cdot r_b^2) \cdot 2 \cdot \dot{\theta}_b$$

$$\frac{\partial L}{\partial \dot{r}_b} = \frac{1}{2} \cdot \left( \frac{7}{5} \cdot 2 \cdot m_s \cdot r_b \right)$$

If we derive both expressions with respect to time  $t$ , we get:

$$\frac{d}{dt} \left[ \frac{\partial L}{\partial \dot{\theta}_b} \right] = (I_b + m_s \cdot r_b^2) \cdot \ddot{\theta}_b + 2 \cdot m_s \cdot r_b \cdot \dot{r}_b \cdot \dot{\theta}_b$$

$$\frac{d}{dt} \left[ \frac{\partial L}{\partial \dot{r}_b} \right] = \frac{7}{5} m_s \cdot \ddot{r}_b$$

The others equations, which we need are:

$$\frac{\partial L}{\partial \theta_b} = -m_s \cdot g \cdot r_b \cdot \cos \theta_b$$

$$\frac{\partial L}{\partial r_b} = \frac{1}{2} \cdot [2 \cdot m_s \cdot r_b \cdot \dot{\theta}_b^2] - m_s \cdot g \cdot \sin \theta_b$$

### EQUATIONS OF MOTION:

$$(I_b + m_s \cdot r_b^2) \cdot \ddot{\theta}_b + 2 \cdot m_s \cdot r_b \cdot \dot{r}_b \cdot \dot{\theta}_b + m_s \cdot g \cdot r_b \cdot \cos \theta_b = \tau$$

$$\ddot{r}_b + \frac{5}{7} \cdot (g \cdot \sin \theta_b - r_b \cdot \dot{\theta}_b^2) = 0$$

where  $\tau$  is the torque applied to the beam.

## Chapter 5

### Modeling in Modelica

In this chapter the two models are written in the Modelica language through equations and another model is created with the Modelica's libraries. We also present simulation results using Dymola for the different models.

#### 5.1 Models with the Modelica language

Modelica is unlike most general-purpose languages not primarily based on algorithms, but uses equations instead, that is one does not need to reformulate the differential equation into the standard form (explicit)

$$\frac{dx}{dt} = f(x, u, t)$$

but can have general equations where the time derivatives appear implicitly. For every model the programmer can define a number of equations describing the properties of the model. The equations define the relation between the different quantities in the simulation.

The main reason why Modelica uses equation is that every simulation problem in fact is a mathematical problem. It also give the language a high abstraction level, because an equation is often more intuitive than an algorithm.

Dymola provides a complete simulation environment. Dymola transforms a declarative, equation based, model description into efficient code. After a model has been translated into simulation code, the simulation run is set up. Parameters and initial conditions are be defined, as well as the duration of the simulation.

Dymola is used to visualize dynamic behavior. Plots of the time-response of variables are often hard to interpret and a more realistic graphical view is needed. Dymola supports a 3-dimensional animated model view in addition to dynamic modeling with a library of graphical objects. When a model is described in Dymola with equations and submodels, it is also possible to define its visual appearance. This is done including predefined graphical objects of various shapes.

The two obtained models in the previous chapter can be written in Modelica through their equations of motion. These two programs are shown below with the respective simulations done with Dymola.

### 5.1.1 Modelica model: Newton's second law

```
model ball_beam_1
import Modelica.SIunits;

// Constants
constant Real g=Modelica.Constants.g_n "Gravitational Acceleration";

// Parameters
parameter Real k=1.0 "Motor constant";

// Variables
Real alpha "Beam angle";
Real v "Velocity of the ball";
Real a "Acceleration of the ball";
Real x "Position of the ball";
Real u "Control signal";
equation

v = der(x);
a = der(v);

// Mathematical modeling
a = (5/7)*g*Math.sin(alpha);
der(alpha) = k*u;

// Control signal
u = 0;

end ball_beam_1;
```

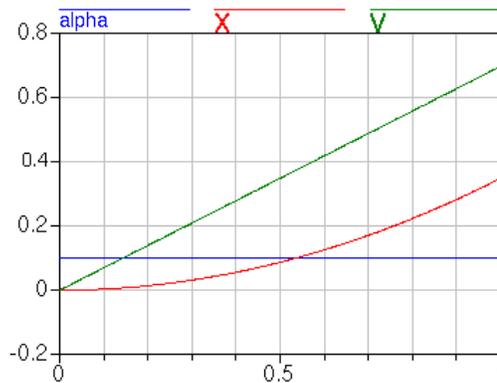


Figure 5.1: Dymola simulation: Response of beam angle, position of the ball and velocity open-loop response for model base on Newton's second law

This model fits well the beam, which is driven via a gearbox, that is the ball position, and the torque the ball causes, does not affect the angle of the beam.

### 5.1.2 Modelica model: Lagrangian method

```

model ball_beam_2
import Modelica.SIunits;

// Parameters
parameter SIunits.Mass m=0.1 "Mass of ball";
parameter SIunits.Length L=1.0 "Beam length";
parameter SIunits.Radius r=0.015 "Radius of the ball";
parameter SIunits.MomentOfInertia J=(2/5)*m*r^2 "Sphere's moment of Inertia";
parameter SIunits.MomentOfInertia I=1e7 "Beam Inertia, value";

// Constants
constant Real g=Modelica.Constants.g_n "Gravitational Acceleration";

// Variables
Real theta "Beam Angle";
Real w "Angular Velocity";
Real alpha "Angular Acceleration";
Real x(start=0.0) "Position the ball in the beam";
Real v "Velocity of the ball";
Real a "Acceleration of the ball";
Real tau(start=0.0) "Torque";
equation

```

```

v = der(x);
a = der(v);
w = der(theta);
alpha = der(w);

// Lagrangian method
(I + m*x^2)*alpha + 2*m*x*v*w + m*g*x*Modelica.Math.cos(theta) = tau;
a + (5/7)*(g*Modelica.Math.sin(theta) - x*w^2) = 0;

// Control law
tau = 0;

end ball_beam_2;

```

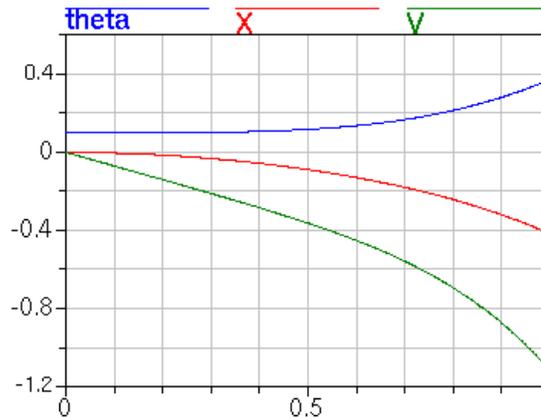


Figure 5.2: Dymola simulation: Response of beam angle, position of the ball and velocity Open-loop response for the Lagrangian model

This model is appropriate for a beam, which is direct-driven from the motor (no gearbox) and easy to move by hand. Therefore the ball position and the corresponding torque due to gravity will affect the beam angle much more.

Both models can be exported to Simulink for either simulation or control design, which is later to be used for the control of the beam and ball process through feedback from a vision system. With this program, running on another computer, we can determine the ball position, which are then sent to the controller via a network connection.

The export of a linearized model to Simulink can be realized from mode Simulation of Dymola. In order to do it, you can use the command Linearize, included in the Simulation Menu. This command calculates a linearized model at some determined initial values. The linearized model is stored in Matlab format and can be loaded into Matlab with the m-file tloadlin.

Another way to do the exportation from Dymola to Simulink can be found in the

Master Thesis Project by Xavier Callier [9] or Francesco Calugi [10].

## 5.2 Model with Modelica's libraries

This section explains another alternative to model rolling on a surface.

The free MultiBody library contains 3-dimensional mechanical components to model rigid multi-body systems, such as robots, satellites or vehicles.

The library provides basic model classes for rigid bodies, joints, forces, measurement and animation elements. Revolute, prismatic and other ideal joints connect bodies. Kinematic loops can be handled by using cut-joints to break the loops.

For a user it is easy to introduce new components or copy and modify existing ones.

A unique feature of the library is the property that joints can have a variable structure. That is, every degree of freedom of a joint can be locked and unlocked during movement without degenerating efficiency.

This library offers an alternative to the ModelicaAdditions.MultiBody library.

The obtained model with Modelica libraries is shown below:

```
model TestSphere
```

```
parameter SI.Acceleration g=9.81;
inner parameter SI.Acceleration[3] Gravity={0,-g,0};
```

```
// Ellipsoid semi-diameters
```

```
inner parameter SI.Length a1=1;
inner parameter SI.Length b1=1;
inner parameter SI.Length c1=1;
inner parameter SI.Angle delta=Modelica.Constants.pi/10;
```

```
Base Base1 annotation (extent=[-60, 0; -40, 20]);
```

```
RollingBody RollingBody1(
q(start={1,0,0,0}),
r(start={0,1,0}),
I=[1, 0, 0; 0, 1, 0; 0, 0, 1],
v(start={0.05,0,0}),
omega(start={-1,-1,-0.05})) annotation (extent=[20, 0; 40, 20]);
Ellipsoid_on_Plane Ellipsoid_on_Plane1 annotation (extent=[-20, 0; 0, 20]);
```

```
equation
```

```
connect(Base1.InPortRoll, Ellipsoid_on_Plane1.OutPortA)
annotation (points=[-50, 19; -50, 30; -13, 30; -13, 19]);
connect(Base1.OutPort, Ellipsoid_on_Plane1.InPortA)
```

```

annotation (points=[-50, 1; -50, -10; -13, -10; -13, 1]);

connect(Ellipsoid_on_Plane1.InPortB, RollingBody1.OutPort)
annotation (points=[-7, 1; -7, -10; 30, -10; 30, 1]);
connect(Ellipsoid_on_Plane1.OutPortB, RollingBody1.InPortRoll)
annotation (points=[-7, 19; -7, 30; 30, 30; 30, 19]);

end TestSphere;

```

For more details please refer to the web page:

<http://www.modelica.org/Conference2003/papers.shtml> [12]

The architecture of information interactions is shown below:

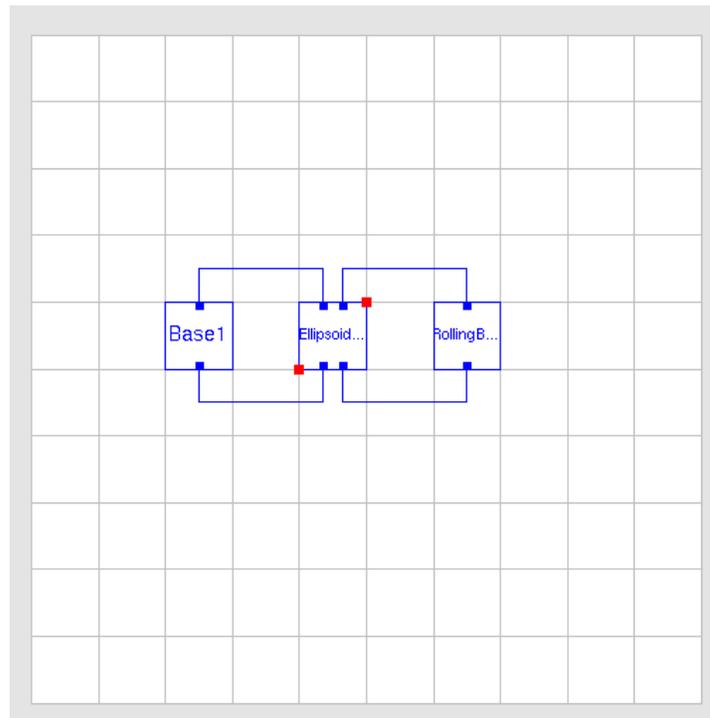


Figure 5.3: Architecture of obtained model with Modelica libraries

One should consider all connectors used above as bidirected ones. Arrows in Figure 5.3 are used to show the semantics of interactions. It's clear that the whole construction considered above is a virtual one. Constructing the model the compiler extracts all equations from the objects and assembles them composing the DAE system optimized for a numeric integrator.

A basic feature is that all components have animation information with appropriate default sizes and colors. A typical screenshot of the animation of beam and ball is shown in the Figure 5.4 below.

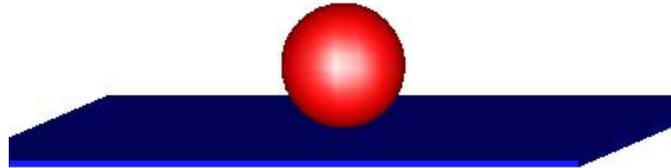


Figure 5.4: Animation of obtained model with Modelica libraries

## Chapter 6

### Control Design and Simulations

This chapter details the control design of the two obtained models with the Modelica language. With the Newton's second law model, we do the study through an observer design and with the Lagrangian model we work with a linearized model and an observer to do the study. In this chapter are also shown the obtained simulations in Simulink.

#### 6.1 Control design

##### 6.1.1 Control design through observer

All states are not available for feedback in many cases and one needs to estimate unavailable state variables. Estimation of unmeasurable state variables is commonly called observation. A device (or a computer program) that estimates or observes the state is called a state-observer or simply an observer. If the state-observer observes all state variables of the system regardless of whether some state variables are available for direct measurement, it is called a full-order state observer.

An observer that estimates less than the dimension of the state-vector is called a reduced-order state-observer or simply a reduced-order observer.

The reason for introducing the observer is that pole placement with full state feedback, is not very practical. First, for an  $n$ -dimensional system, it requires  $n$  measurements, which, in turn, means  $n$  transducers. Such a controller would be both expensive and bulky. Further, to be implementable all the states would have to be measurable. Even if such a state model formulation could be obtained, it might not be a preferred formulation.

Basically, there are two forms of the implementation of an estimator as open loop and closed-loop. The difference between these two is a correction term, involving the estimation error, used to adjust the response of the estimator. A closed-loop estimator is referred to as an observer.

Because of our Ball and Beam model is open loop unstable, is necessary to have some kind of measurement of the ball velocity. The classical proportional PD-controller gets a velocity measure by differentiating the ball position. The classical phase lead compensator does something very similar. Another way of doing this is to use an observer based upon a model of the ball and beam to estimate the systems states, and use the state estimates (of ball position and velocity) in a state feedback controller.

We design a full-order state observer to estimate those states that are not measurable. We want to do our observer as fast as it is possible, without amplifying too much high frequency disturbances. Therefore we place the poles of the observer in the range of two to five times larger in magnitude than the controller poles.

With our controller we want to get that the system is stable. Below a schematic of our plant-observer and controller system is shown.

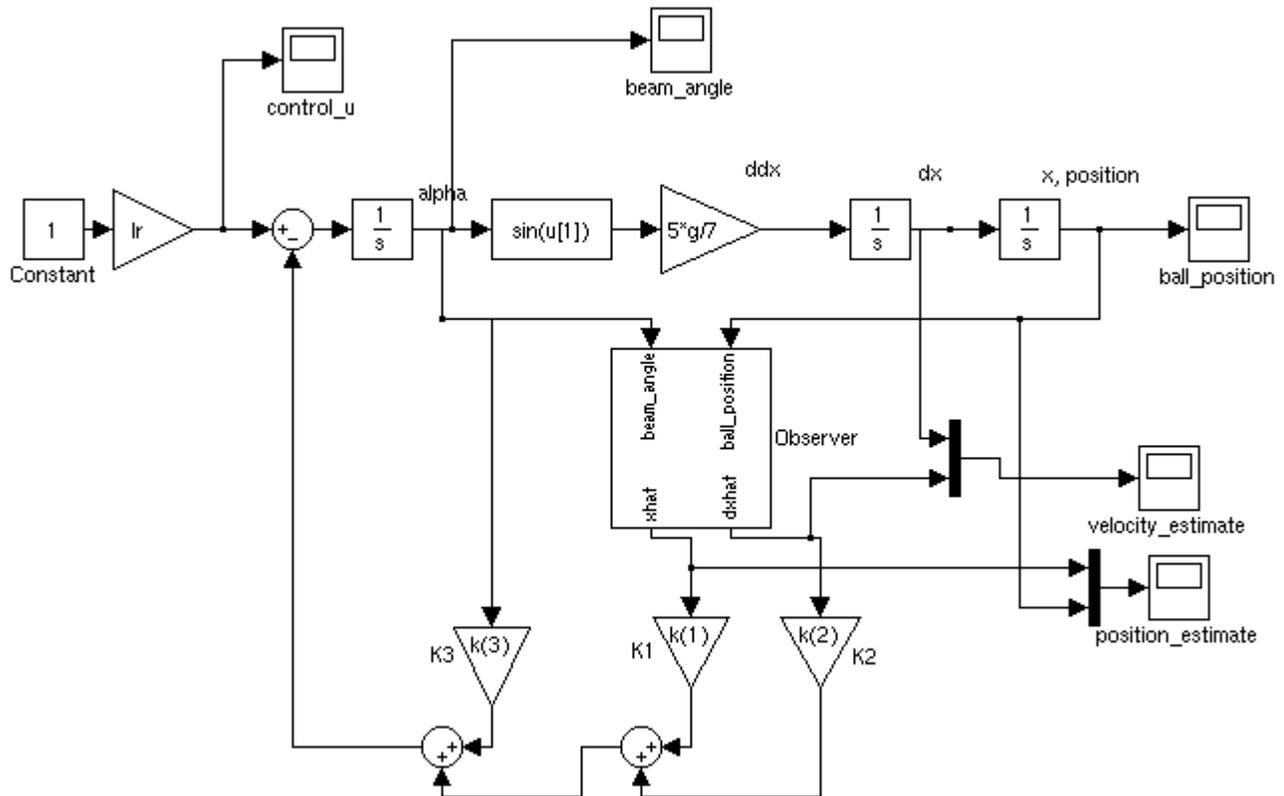


Figure 6.1: Simulink: Newton's second law model; plant-observer and controller

### 6.1.2 Control Design: nonlinear system

Considering the obtained equations of motion in section 4.1.2, we do a study of control design through a linearized state model of the system around a equilibrium position. We also obtain a stabilizing controller for the linear model, when the angular position is measured.

The equations of motion were:

$$(I_b + m_s \cdot r_b^2) \cdot \ddot{\theta}_b + 2 \cdot m_s \cdot r_b \cdot \dot{r}_b \cdot \dot{\theta}_b + m_s \cdot g \cdot r_b \cdot \cos \theta_b = \tau$$

$$\ddot{r}_b + \frac{5}{7} \cdot (g \cdot \sin \theta_b - r_b \cdot \dot{\theta}_b^2) = 0$$

The nonlinear states are:  $\theta_b$ ,  $\dot{\theta}_b$ ,  $r$  and  $\dot{r}$

and the state equations become:

$$\begin{cases} \frac{d\theta}{dt} = \dot{\theta} = f_1 \\ \frac{d\dot{\theta}}{dt} = \ddot{\theta} = -\left(\frac{2 \cdot m_s \cdot r_b}{I_b + m_s \cdot r_b^2}\right) \cdot \dot{\theta} \cdot \dot{r}_b - \left(\frac{m_s \cdot g \cdot r_b \cdot \cos \theta_b}{I_b + m_s \cdot r_b^2}\right) + \left(\frac{1}{I_b + m_s \cdot r_b^2}\right) \cdot \tau = f_2 \\ \frac{dr}{dt} = \dot{r} = f_3 \\ \frac{d\dot{r}}{dt} = \ddot{r} = \frac{5}{7} \cdot r_b \cdot \dot{\theta}_b^2 - \frac{5}{7} \cdot g \cdot \sin \theta_b = f_4 \end{cases}$$

To have a desired equilibrium in:

$$\begin{array}{ll} \theta_e = 0 & \dot{\theta}_e = 0 \\ r_e = 1 & \dot{r}_e = 0 \end{array}$$

we thus define the states a,

$$\begin{array}{l} x_1 = \theta - \theta_e = \theta \\ x_2 = \dot{\theta} - \dot{\theta}_e = \dot{\theta} \\ x_3 = r - r_e = r - 1 \\ x_4 = \dot{r} - \dot{r}_e = \dot{r} \end{array}$$

and the control input,

$$u = \tau - \tau_e$$

By substituting values in  $f_2$ , we obtain:

$$\tau_e = m_s \cdot g \cdot r_e$$

working with these new values in the state equations and considering the equilibrium,  $x_1=x_2=x_3=x_4=u=0$ , we thus have the linearized state model:

$$\begin{aligned} \dot{x} &= A \cdot x + B \cdot u \\ y &= C \cdot x \end{aligned}$$

where  $x$  is a vector representing the state,  $u$  is a scalar representing the input and  $y$  is a scalar representing the output. The matrices  $A$ ,  $B$  and  $C$  determine the relationships between the state and input and output variables.

In our system the matrices  $A$ ,  $B$  and  $C$  have the following representation:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{-m_s \cdot g}{I_b + m_s} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{-5}{7} \cdot g & 0 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 1 \\ \frac{1}{I_b + m_s} \\ 0 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

The next step is to check the controllability and the observability of the system. For the system to be completely state controllable, the controllability matrix

$$Q_c = [B \quad AB \quad A^2B \quad A^3B]$$

must have the rank of 4. The rank of the matrix is the number of independent rows (or columns). In the same way, for the system to be completely state observable, the observability matrix

$$Q_o = \begin{bmatrix} C \\ CA \\ CA^2 \\ CA^3 \end{bmatrix}$$

must also have rank of 4.

To obtain a stabilizing controller for the linearized model, we need to have a stable characteristic polynomial for the closed loop system (roots strictly in the left half-plane). In this example we determine a state-feedback gain ( $k$ ) such that the closed-loop poles are at  $s=-1$  (order 4). The characteristic polynomial is:

$$\alpha_c(s)=(s+1)^4=s^4+4s^3+6s^2+4s+1$$

$$\alpha_c(A)=A^4+4A^3+6A^2+4A+I$$

Thus, by Ackermann's formula,

$$k = [0 \ 0 \ 0 \ 1] \cdot Q_c^{-1} \cdot \alpha_c(A)$$

where,  $Q_c$  is the controllability matrix previously defined.

We place the poles of the observer in  $s=-5$ , that is five time bigger than our controller poles, with it we get that our system is faster. Thus, we have:

$$\alpha_o(s)=(s+5)^4=s^4+20s^3+150s^2+500s+625$$

$$\alpha_o(A)=A^4+20A^3+150A^2+500A+625I$$

Thus, by Ackermann's formula,

$$L = \alpha_o(A) \cdot Q_o^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

where,  $Q_o$  is the observability matrix defined before.

Thus, we have the observer feedback controller,

$$\begin{aligned} \frac{d\hat{x}}{dt} &= (A - B \cdot k - L \cdot C) \cdot \hat{x} + L \cdot y \\ u &= -k \cdot \hat{x} \end{aligned}$$

The following Simulink model can be used to simulate the system.

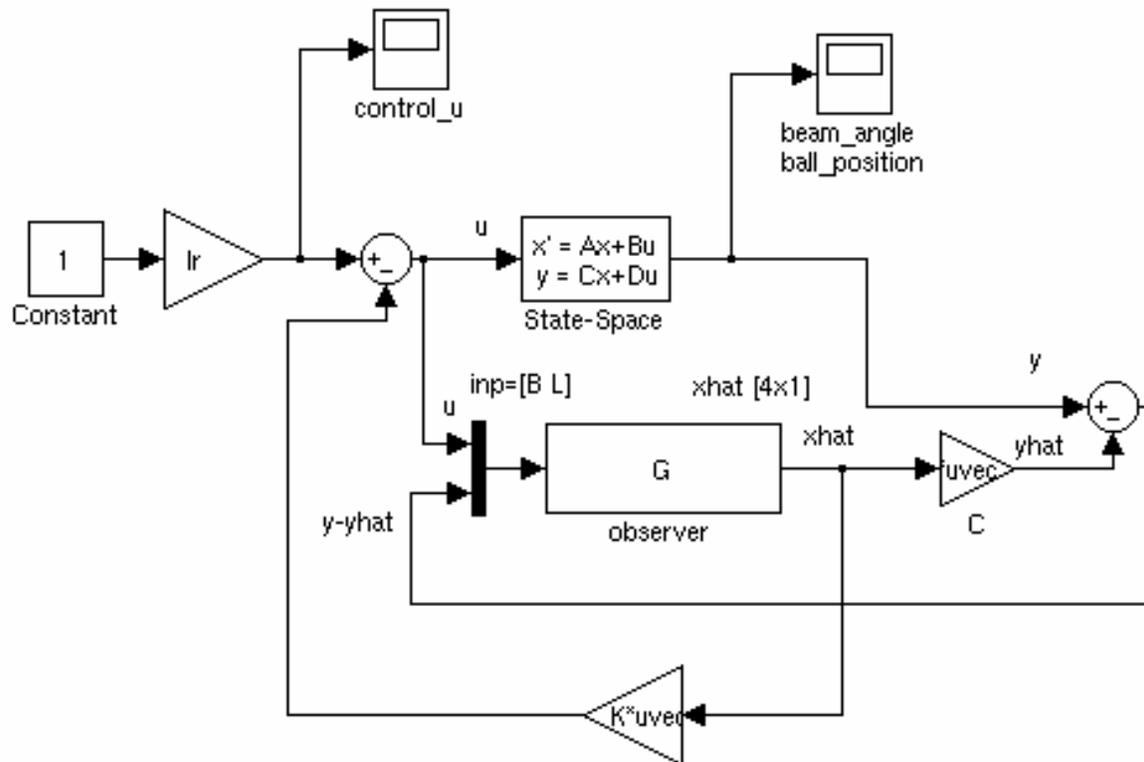


Figure 6.2: Controller of linearized Lagrangian model in Simulink

## 6.2 Simulations

### 6.2.1 Simulations in Simulink

Simulink is an interactive environment integrated in Matlab for modeling, simulation and analyzing dynamic systems. Simulink provides a graphical user interface for constructing block diagram models via drag and drop operations. Models can be grouped into hierarchies to create a simplified view of components or subsystems. Therefore a model built up in Simulink consists of blocks that correspond to subsystems of the model. In each block there are mathematical relationships that describe the physical behavior of the system. If the subsystems affect each other, information between the blocks has to be exchanged in order to evaluate the relationships.

The benefit with Simulink is the easy to use design and since the software is integrated with Matlab it makes it very powerful with a lot of useful analysis and design applications.

Another benefit is the easy way to create plots of signals. Further, the ability to easily and quickly simulate a model built in Simulink is another benefit with this modeling program.

However it lacks the benefits of Modelica to define implicit equations and relationships.

➤ Control design through observer

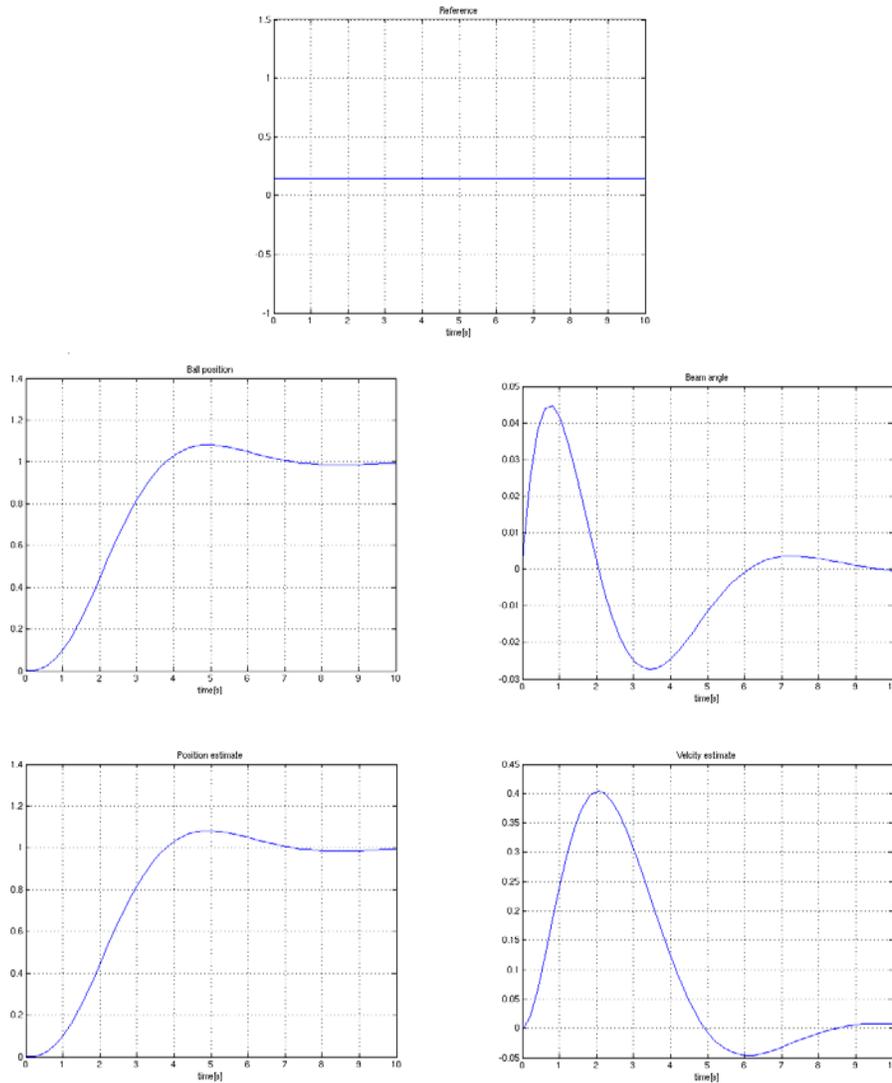


Figure 6.3: Simulations obtained with the Newton's second law model and observer

In Figure 6.3 we can see the behavior with the calculated controller and observer. The closed loop system behaves well.

We can observe how the position and the position estimate of the ball are almost the same. Both responses are stabilized at 1 like the reference, and besides we can see that the beam angle and the velocity estimate are stabilized in few seconds.

## **Chapter 7**

### **Experiments**

This chapter describes the experimental setup for the Ball and Beam experiments. Initial experiments are performed to identify process parameters and finally the control experiments are performed. An alternative implementation to the one described in Chapter 6 is presented.

#### **7.1 Experimental Setup**

We use the ball and beam process shown in Figure 7.2. The beam is controlled by a DC-motor and the beam angle can be measured. The ball position is estimated from a vision system written by Tomas Olsson, PhD student at the Department of Automatic Control and uses a Fire-i camera connected to a PC running a “ball detection” program. The ball coordinates are sent via a network connection to a Linux PC running the control implementation in a real-time extension of Matlab/Simulink developed by A.Blomdell. A sketch of the connections can be visualized in Figure 7.1.

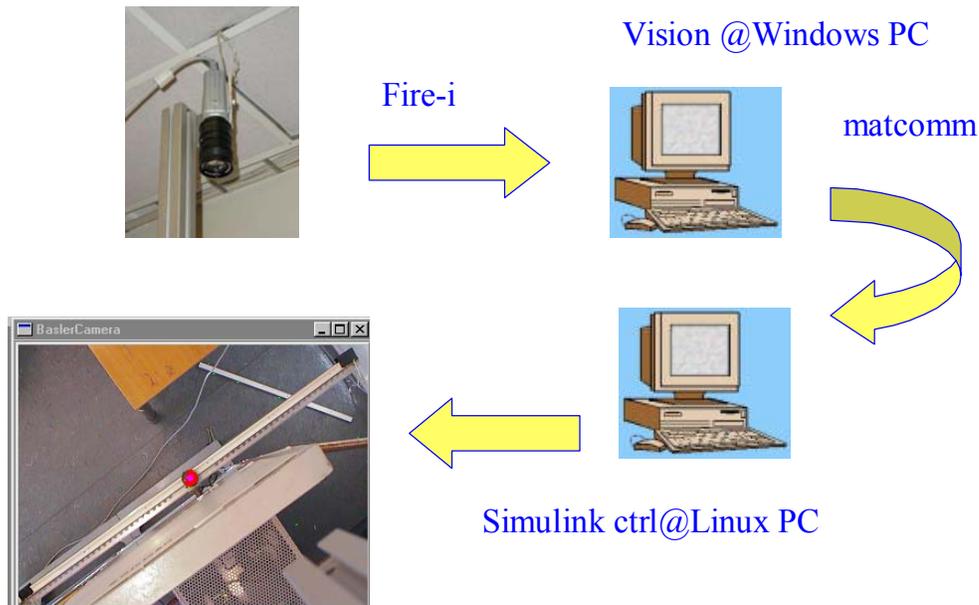


Figure 7.1: Sketch of the connections between used ball and beam, vision system and PC's

## 7.2 How to do the experiments

The first task in this work consists of determining which is the correct model of the real process of the ball and beam, including finding appropriate parameters. To find this correct model, we do some experiments with the real process. The “ball and beam”-process is shown below and the controller is implemented in Matlab/Simulink with a real-time extension, where a Simulink block represents the connection to analog inputs and analog outputs, see Figs. 7.2 and 7.3.



Figure 7.2: Ball and Beam used

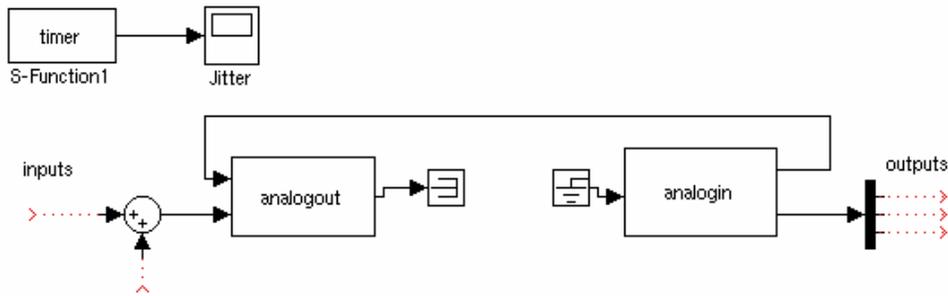
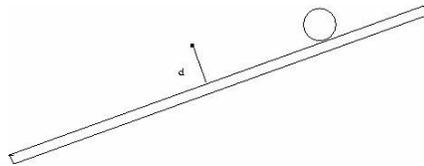


Figure 7.3: Controller of the Ball and Beam process

### Beam-angle dynamics

The beam is directly connected to a DC-motor without any gearbox according to Fig. 7.4. Here we can note that there is a distance,  $d$ , between the motor axis and the beam. This will make the beam oscillate like a pendulum if no control signal,  $u$ , to the motor, is applied, and thus we can expect an oscillatory behavior. We will first do a simple experiment to find out the eigenfrequency and possible damping of this motion. The next step is to find the gain from commanded control signal in the Simulink model to the motor torque and to the process output (beam angle).

Figure 7.4: Ball and beam with distance  $d$ 

We first start with applying an impulse disturbance to the uncontrolled beam for an initial angle=0. The input signal proportional to the beam angle is shown in Fig.7.5.

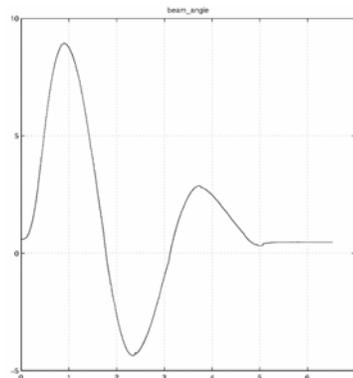


Figure 7.5: Response of the beam with applied impulse

The period time of the oscillation is approximately 3 seconds, therefore the frequency  $\omega \approx 2\text{rad/s}$ . Now that we have our frequency, we can find which are our damping and our overshoot.

With these values and using tools of Matlab we can observe the impulse response of the system being this shown in the Fig 7.6:

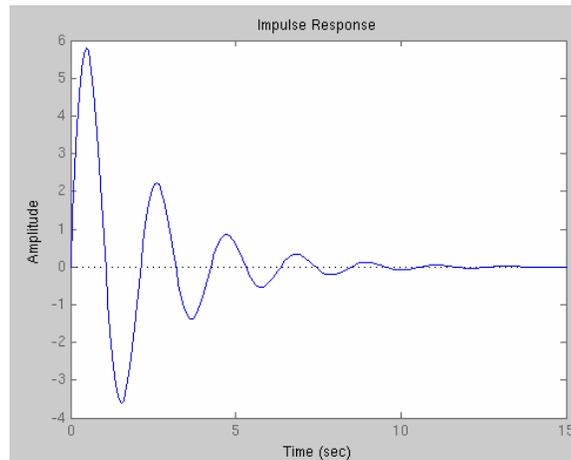


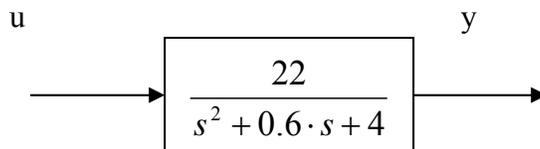
Figure 7.6: Impulse Response of the Ball and Beam process

We can observe from the response, that there is an additional damping and an oscillatory behavior, in comparison what we have discussed previously.

From Figure 7.6, we can estimate the impulse response correspond to a system, which transfer function has a gain  $\approx 22$ . This gain has been calculated through of the Figure 7.5.

$$G = \frac{22}{s^2 + 0.6 \cdot s + 4}$$

Through this transfer function, we can represent the system in state-space form, doing it the following way:



$$s^2 \cdot y + 0.6 \cdot s \cdot y + 4 \cdot y = 22 \cdot u$$

we have  $x_1=y$ , then the state equations are:

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= \ddot{y}\end{aligned}$$

substituting:

$$\begin{aligned}\dot{x}_2 &= \ddot{y} = -0.6 \cdot \dot{y} - 4 \cdot y + 22 \cdot u \\ \dot{x}_2 &= -0.6 \cdot x_2 - 4 \cdot x_1 + 22 \cdot u\end{aligned}$$

The state-space representation is shown below:

$$\begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -4 & -0.6 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 22 \end{bmatrix} \cdot u \\ y = [1 \quad 0] \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{cases} \quad (7.1)$$

To do the study of the system we write an m-file in Matlab. In this m-file we include the matrices of state-space system and the obtained values of desired frequency and damping. With these values we can calculate the desired roots of our system.

Now we have our poles, we can use Matlab to find a controller (k matrix) by using the *place* command, see Chapter 6.

To implement our controller we have to find an observer, which can do an estimation of the unmeasurable state variables. Normally the poles of the observer are faster than those of the controller. We place the poles two times faster than our controller. The observer is basically a copy of the plant; it has the same input and almost the same differential equation. An extra term compares the actual measured output  $y$  to the estimated output  $\hat{y}$ ; this will cause the estimated states  $\hat{x}$  to approach the values of the actual states  $x$ . The error dynamics of the observer are given by the poles of  $(A-L \cdot C)$ . In the same way as before with the command *place* we find the observer (L matrix).

The next step is to do the Simulink model with the plant of the real process and the obtained observer and controller. This Simulink model is shown in the Fig 7.7.

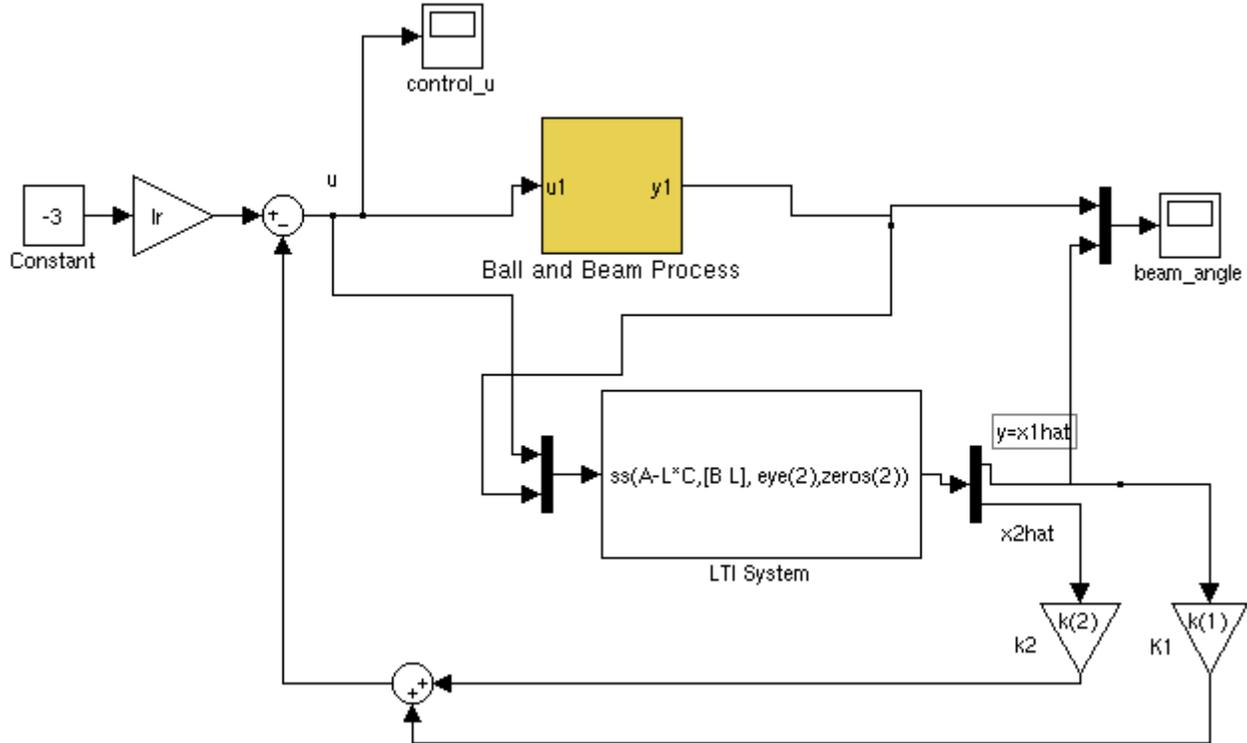


Figure 7.7: Simulink model of observer based control of beam angle

We can now simulate the closed-loop response and we can check if the found model is correct. Changing the values the  $w$  we can observe if the system is faster or slower and we can see if its behavior is right. We can also change the values of the inputs to check if the response of the real process is correct in every moment.

A design problem does not necessarily have a unique answer. Using this method (or any other) may result in many different compensators.

For the implementation to control the real process we use a discrete-time feedback from an observer based on a sampled version of the system 7.1.

We have used the Matlab command `c2d` to convert between continuous and discrete time. The sampling time for the Simulink controller was set to 10ms. The poles of the discrete-time design (used in *place*) was transformed from continuous-time specifications according to  $\text{disc\_pole} = \exp(\text{cont\_pole} \cdot \text{tsamp})$ .

Ball controller

For the real-time implementation of the ball controller we have chosen to do a cascade-design, re-using the beam-controller from the previous subsection for the inner loop, instead of the controlled presented in Chapter 6.

The coordinates of the ball from the vision systems are updated with 30Hz. However the camera pictures may be delayed  $\geq 30\text{ms}$  in the controller and the camera is not synchronized with the rest of the controller. To handle this uncertainty we have chosen to run a faster inner loop and an outer-loop with a slower sampling rate.

From Chapter 4, we have an approximate model of a double integrator from beam angle to ball position, and we start to do a simple experiment to find out the gain with respect to the position provided by the vision system. We can visualize it in the figure 7.8.

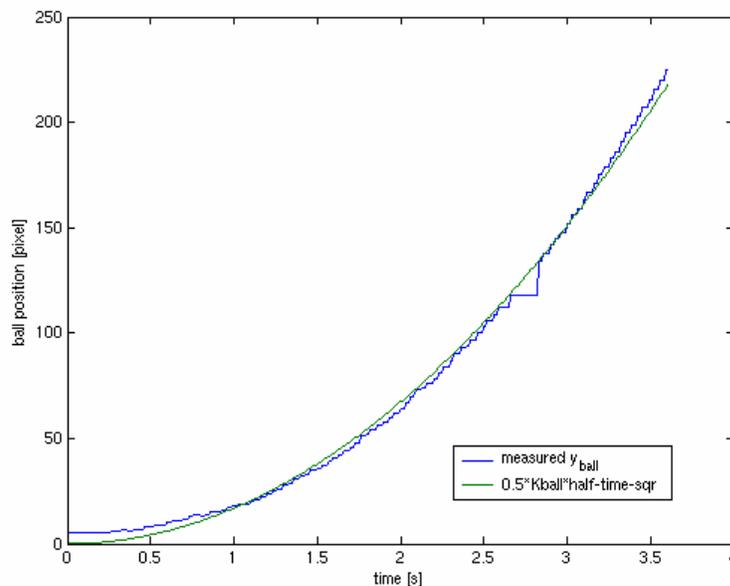


Figure 7.8: Graphic to find out the gain with respect to the position provided by the vision system

A video sequence of the experiment can be found at [13].

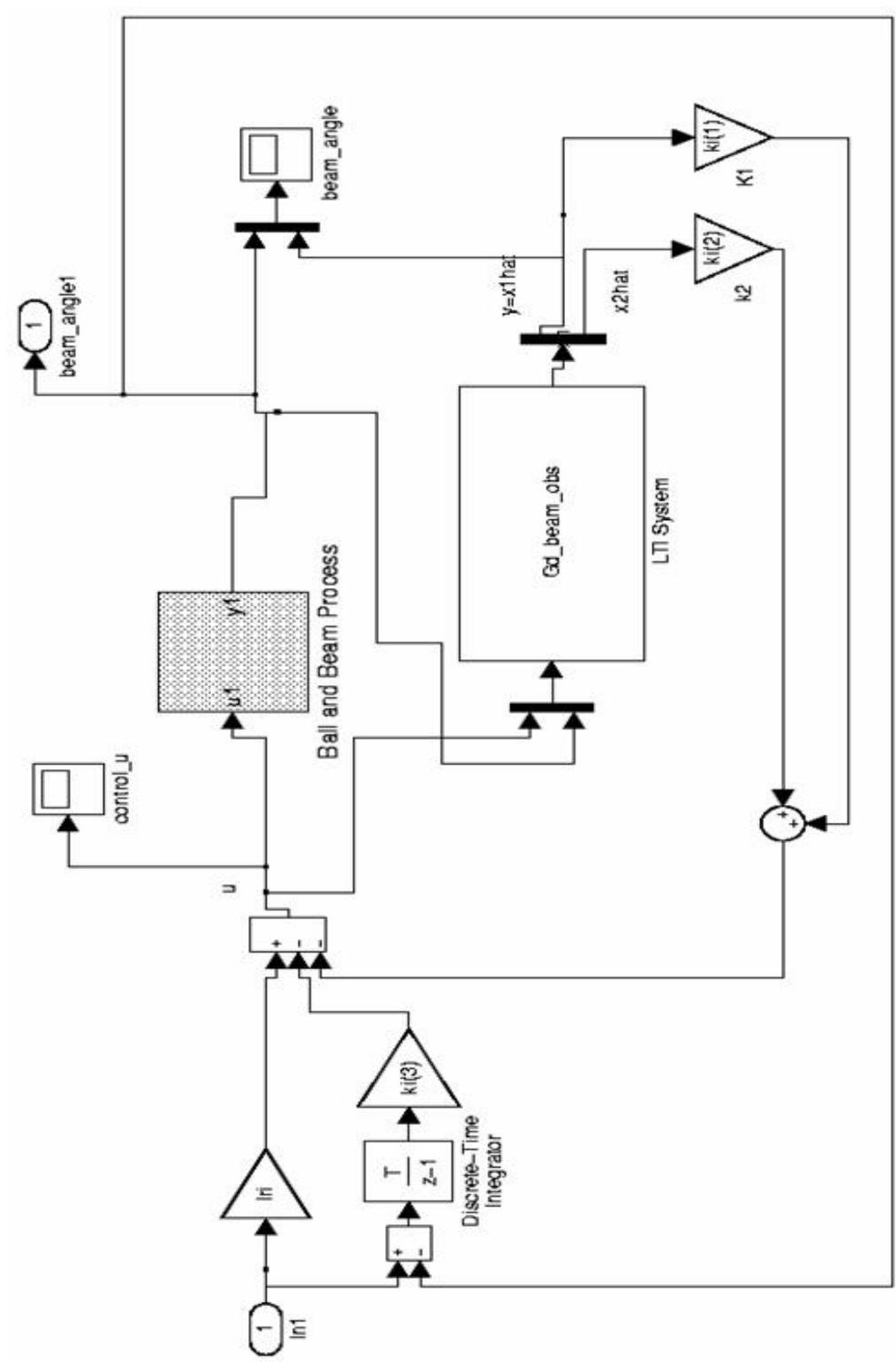


Figure 7.9: Simulink model to do the beam control

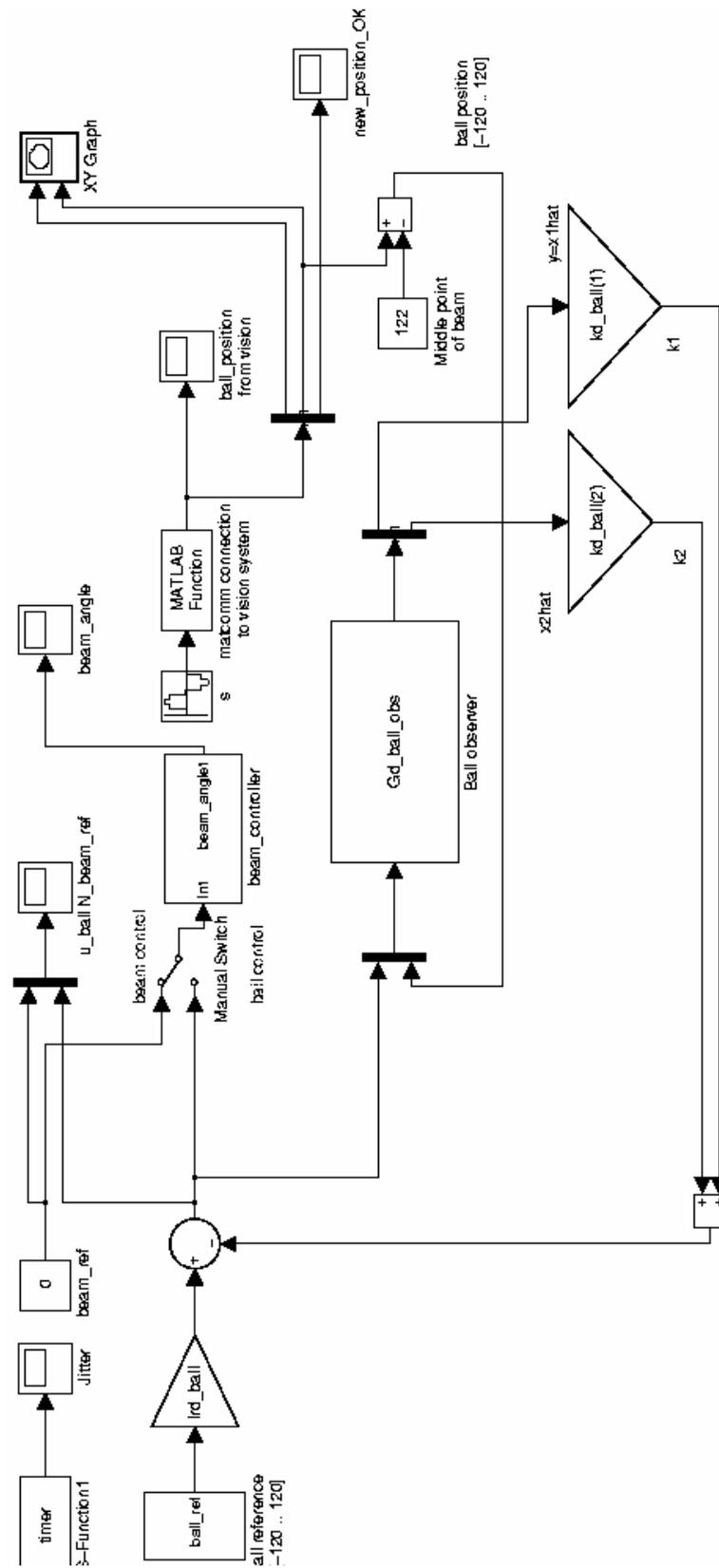


Figure 7.10: Simulink model to do the ball position controls through the vision system

## **Chapter 8**

### **Conclusions**

In this chapter the conclusions of this work are presented followed by suggestions on how to continue the development.

#### **8.1 Conclusions**

The main goal of this thesis was to do the modeling and control of the Ball and Beam process. This objective has been fulfilled by the presentation of several kinds of control, which have been done through Modelica and Matlab and finally by experiment on the real process.

Over this thesis we can visualize how control theory relates to real systems. Computer simulations can help, but simulations alone are limited by how well the system in question has been modeled. It is more enlightening if the results obtained theoretically are actually applied to a physical system. Applying the theoretically calculated results to a real system helps us not only visualize, but to evaluate how well the model was able to predict the system performance.

The best way to learn about control systems is to design a controller, apply it to the system and then watch the system in operation. A system is modeled on a computer, and, with the help graphics, the system can be seen in action. However, the system being observed in the simulation is in reality just a model of the true system. The model must always be a simplified representation of the system, and cannot reproduce all aspects of system behavior. Such effects are difficult to simulate, and are best understood from hands-on experience with the physical system.

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