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IMPLEMENTATION OF BALL-AND-BEAM CONTROL SYSTEM AS AN INSTANCE OF SIMULINK TO 32-BIT MICROCONTROLLER INTERFACE

A ball balancing on a beam is a perfect platform for demonstration various control strategies. The task is to place ball rolling freely, in a reference position along the beam driven by a motor, rejecting disturbances. The research system consists of mechanical platform with stepper motor and two infrared ball position sensors, power supply and electronic controller based on a 32-bit microcontroller connected to Matlab/Simulink software running the main control algorithm. Designed in Simulink input and output subsystem blocks contain all functions required to provide data exchange with microprocessor controller of the mechanical system. Developed data exchange protocol and its implementation both in microcontroller software and Simulink subsystems allow to use this complete system for educational purposes: the controller designer is free to develop supervisory control layer, not going into details of system operation. The results of system operation with P, PD and LQR control laws are shown at the end of this paper.

1. INTRODUCTION

Modern university courses of control theory should not focus only on control systems simulations and textbook computational exercises. There is a rising demand on impressive laboratory systems that can be easily configured and reprogrammed for work with user-defined control strategies to develop students engineering abilities. An objective of the design and research work described in this paper was to develop a laboratory control system with an interface to Matlab computing environment. The main requirements were following: interface that allows to implement control laws in an easy manner (graphical user interface is preferred), compact size, low cost, simple design, minimized number of sensors, education purpose. The presented ball-and-beam laboratory system satisfied these conditions. This system is unstable, underactutated and nonlinear and therefore it is appreciated as a benchmark for various control strategies. It can be easily adapted as control theory laboratory exercise for Control Engineering, Computer Science or Electrical Engineering students.

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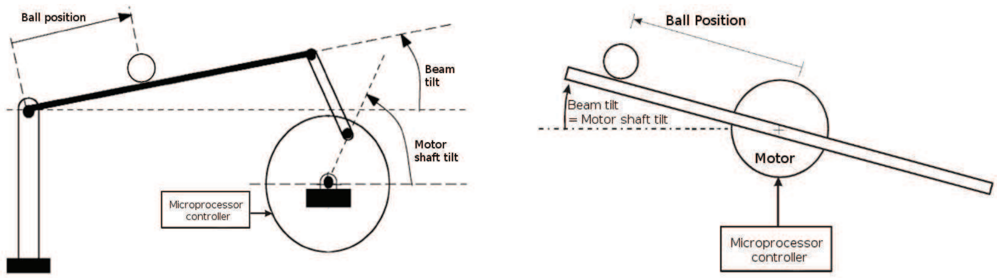
The system consists of a ball rolling freely on a beam, which is driven by an electric motor. The task is to keep the ball in one reference position rejecting disturbances or to track the reference position signal. Both accuracy and dynamic aspects of control need to be taken into consideration during design of the control strategy.



(a) (b)

Fig. 1. Two basic layouts of ball-and-beam system: a) beam driven by a rod, b) motor shaft placed in the center of beam

2. LABORATORY SYSTEM

2.1. Mechanical System

The main principle of the mechanical construction layout is shown in the Figure 1a. One end of the beam is attached to a motionless rod, and the second one is connected to a moveable rod attached (length L) to a disc (diameter $2R$) driven by the motor. All joints are fitted with ball bearings. This layout ensures much better accuracy of the beam positioning than a solution with a motor shaft placed in the center of the beam (figure 1b). For small tilt angles, the relationship between motor shaft position α and beam inclination β in the chosen layout of the system is given by formula 1.

$$\beta = \frac{R}{L}\alpha \tag{1}$$

The presented ball-and-beam mechanism was constructed after complex analysis of the system operation based on model developed in Matlab/Simulink environment. The model of ball movement was derived from the Lagrange-Euler equations, presented in [1]. Due to complicated structure of the mechanical construction, the beam driving system (kinetic chain between motor and beam) was modeled using Simscape SimMechanics blocks, that contain basic parameters of system bodies.

The electrical stepper motor chosen to drive the beam, was simulated using equations presented in [2]. The input vector of the motor model contains momentary rotational speed and position of the motor shaft, as well as voltages of the motor phase windings. Both mechanical and electromagnetic phenomena were taken into consideration within this model. Torque signal is the output of the model. Torque is further multiplied by the gear coefficient and then comes as an input to the described SimMechanics model.

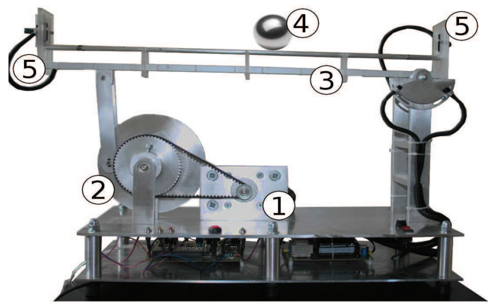


Fig. 2. Overview of the built laboratory system: 1 – stepper motor, 2 - disc connected to the beam by a rod, 3 – beam, 4 – ball, 5 - infra-red position sensors

Some basic control strategies was implemented as the controller of this simulation model, i.e. P, PD and LQR control laws. Beside the control of the position of the ball, it is also essential to bring the velocity to zero. Therefore the most simple proportional controller does not allow to stabilize the ball in a reference position.

Taking into consideration results of the above simulation analysis, the laboratory system mechanism was designed and built. The model was used to choose an optimal electrical motor for this system, as well. The overview of the construction is shown in the Figure 2. Further mechanic details can be found in [3].

2.2. Microprocessor Controller

The heart of the microprocessor controller of the laboratory system is STM100RB microcontroller. The following operations are the main tasks of this 32-bit ARM architecture device: driving the stepper motor, measurement of the ball position and communication with supervisory control layer, i.e. computer with running Matlab/Simulink model. The microcontroller drives the motor by A4988 integrated circuit, that contains in one package translator and MOSFET H-bridge. Therefore, all signals that microcontroller sends to A4988 driver are: selection of the step divider (configured once at the system startup, 3 lines), direction and step impulses (two lines). Both switching between phases and motor current control are provided by the driver. In the presented application, the maximum velocity is limited to 28 deg/s to avoid losing steps. The selected microstep precision is 1/16 of a full step.

The ball position measurement is based on two GP2Y0A41SK0F infra-red analogue position sensors placed at the ends of the beam. The redundancy within the number of sensors is related with small operation distance of these devices. The other disadvantages of these infra-red sensors, such as long reaction time (about 30 ms) and small precision of resistive opto element (low-budget substitute of CCD) are compensated by very low price.

Communication with computer is running by UART interface of the microcontroller. Since most of modern computers is not equipped with any RS-232C port, the common translator MAX232 was replaced by FT232RL. This device uses physical layer of USB interface, but reports in operating system of a computer as a virtual serial port. This way the simplicity of UART usage and its very good Matlab implementation may be combined with universality of USB interface.

3. DATA EXCHANGE PROTOCOL

3.1. Data frame and data exchange cycle

As it was mentioned before, the microcontrollers tasks focuses on acquisition of ball position and stepper motor positioning. Whole algorithm of ball positioning and control law may be easily implemented and changed in real time in the running Simulink-designed algorithm, using GUI. This user-friendly operation is ensured by an effective data exchange protocol.

There are three different types of frames included in the presented protocol. Each communication cycle is initiated by the computer, which works as a client, connected to microprocessor controller working as a server. The initiation frame contains two bytes, representing values threaten in any other frame as inadmissible. If no answer has been received, the initialization is being repeated periodically.

The response of microcontroller to the initial frame contains six bytes of data: two integer values of measurements of voltage outputs of the ball position sensors and momentary position of stepper motor shaft. It is worth to indicate, that application of stepper motor eliminated the necessity of use a closed control loop in motor shaft position control. It simplified the construction of laboratory system: no encoders are necessary. The momentary position of the shaft is simply estimated by counting the number of step impulses, taking into consideration, that conditions of motor operation (limited rotational speed, small torques required to pull up or hold the beam) do not allow to lose steps.

After receiving that frame, Matlab control algorithm computes new reference motor shaft position. This information is sent to microprocessor system as a twobyte integer number, equal to number of microsteps of the motor shaft. Simple diagram in the Fig. 3 recapitulates the data exchange order.

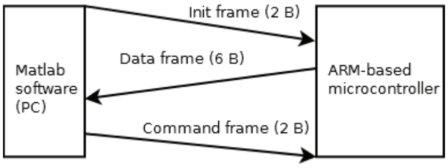


Fig. 3. Diagram of data exchange protocol

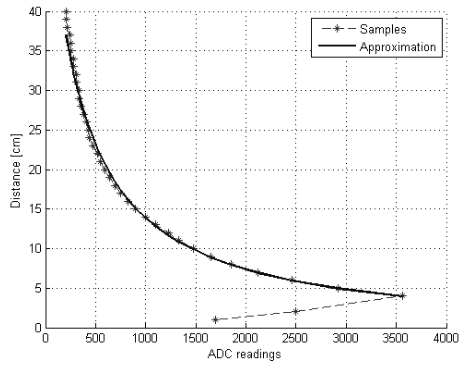


Fig. 4. Non-linear, ambiguous ball position sensor characteristic and its approximation

3.2. Matlab Implementation

The Matlab implementation of the interface focuses on use of Simulink blocks from Instrumentation Control Toolbox. Incoming data are collected by *Query Instrument* block, the new reference shaft position is sent by To Instrument block. The basic configuration of both of these blocks is similar: a valid serial port number and baud-rate have to be selected. An important thing is to set a small incoming and sent data buffer size. If the buffer size is greater than 20 bytes, the software tends to fill the buffer firstly, rather than provide new data to the interface. This makes the communication too slow to control the ball position, since transmission of new reference values to microcontroller becomes too delayed.

Incoming data received by the *Query Instrument* blocks form a buffer, that needs to be split into particular values. It is done by *Unbuffer* blocks, that divide each frame into three values described in section 3.1. The motor shaft position can be easily computed to the angular position in degrees, but the ball position needs more specific operations to be estimated, since the position vs. voltage characteristic is strongly non-linear (Fig. 4). The best results gives inversion combined with 2nd degree polynomial approximation. Moreover, the characteristic is ambiguous – therefore, all the measurements are treated as larger than 4 cm. Data received from two sensors are compared, and the measurement with higher voltage value is taken into consideration, since it indicates, that the ball is closer to this sensor. All the mentioned preprocessing operations are gather in one subsystem, which structure is shown in Figure 5. This subsystem, combined with appropriately configured *To Instrument* block, allow to design own control algorithms, not going into details of system operation. The examples are shown in section 3. Real transmission speed is 125 communication cycles per second – it is over three times faster than the response time of the infra-red position sensors.

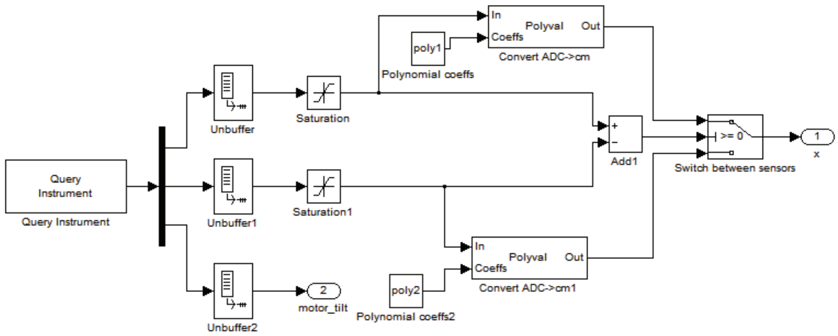


Fig. 5. Simulink subsystem for received data pre-processing

4. TESTS OF A COMPLETE CONTROL SYSTEM

The most satisfactory results of laboratory system examination were obtained using LQR control law. Subsystems described in section 3.2 was utilized as a hardware abstraction layer, all other blocks are standard Simulink operations. Calculation is run in constant-step mode, all blocks were discrete-time elements.

Since the linearized model of the process includes only two state variables (position and velocity of the ball, gathered in state vector $\underline{x}$), the two-element $\underline{K}$ gain vector is required to be used in an implementation of LQR control law, given by a general equation 2.

$$u = -\underline{K}^T \cdot \underline{x} \tag{2}$$

Position of ball is just multiplied by the first element of $\underline{K}$ vector. Velocity of the ball is computed as a difference of momentary positions, filtered by a running average filter with transfer function given by the equation 3.

$$G_f(z^{-1}) = \frac{\sum_{n=0}^{N-1} z^{-n}}{N} \tag{3}$$

The horizon of the filter N is set to 50 samples, due to presence of significant disturbations in infra-red sensor measurements. These two values are summed and then filtered again before being sent. The results of operations with two $\underline{K}$ different values are shown in Figure 6.

Besides the LQR control law, proportional and proportional-derivative control algrorithms were tested. As it was mentioned in section 2.1, P controller is too simple to lead the ball to the reference position. In this control algorithm the ball velocity is not taken into consideration. When the ball passes rolls over the reference position, its velocity is too big to be reduced by the small tilt of the beam. Therefore, the control system including proportional control law is remains unstable (Fig. 7a).

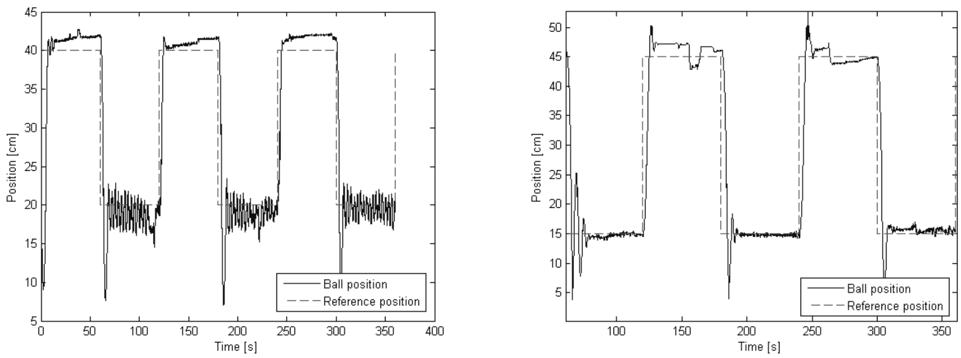
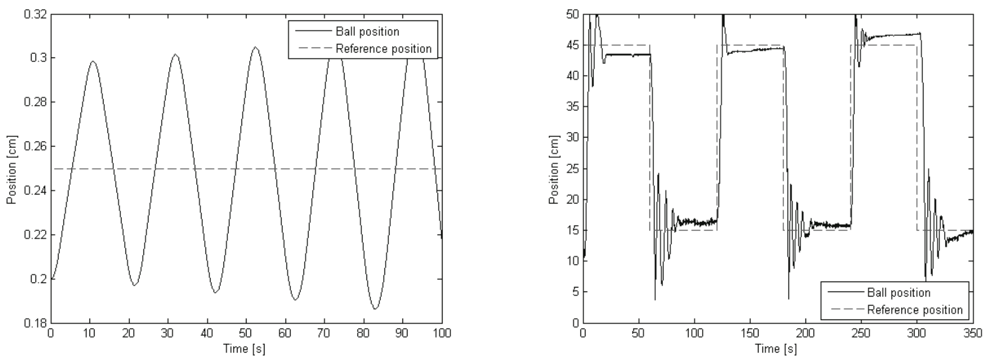


Fig. 6. Test of LQR control strategy with two $\underline{K}$ vector values



(a) (b)

Fig. 7. Tests of basic control strategies: a) proportional control law, b) proportional-derivative controller

System operation with PD and LQR control laws are very similar. Both of them control position and velocity of the ball alike. Application of LQR algorithm provides a second degree of freedom. It is noticeable in step switches between reference position. When the switch occurs, PD controller produces an impuls in output control signal, which cause oscillations and therefore need to be filtered in further processing. Beside this disadvantage, effectiveness of these control laws is comparable.

5. CONCLUSIONS

The objectives of the design and research work has been reached. The laboratory system including hardware and software parts has been designed and launched. An inexpensive platform that can be utilized for educational purpose has been built and basic control algorithms has been tested. These algorithms can be utilized as one of first exercises in laboratory collage course. During system operation no problems with communication has been encountered. The main disadvantages, i.e. slow position sensor response and small accuracy, are related with application of low-cost infra-red sensors.

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