A Position Control Design Module for the CDEN Flexible Cut-off Saw Project

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Abstract

In this paper we provide a summary of our work on one aspect of the CDEN flexible cut-off saw design project. This work focuses on the design and testing of a position control system for DC servo motors. As part of the testing process, a simplified experimental prototype was developed, and the results of the tests with this prototype are described. The paper concludes with a summary of the work that is currently underway on the development of CDEN design modules based on this aspect of the project.

1. Introduction

This paper focuses on one aspect of the CDEN Cut-off Saw Tier 3 design project [1]. This project is aimed at the second or third year student in general engineering, mechanical or electrical engineering programs and at students in the final year of production/industrial engineering programs. The focus of the module is on flexible cut-off saw system capable of varying degrees of complexity (e.g., straight cut to length to multiple axis of control) that will introduce students to basic drive systems, position and velocity measurement, simple logic, state machines and PLCs (programmable logic controllers), basic manufacturing issues (cutting, clamping, etc.), and safety issues in machine design.

In this paper, we describe the design of the positioning control system for the cut-off saw system. In its simplest form, this system is responsible for controlling the rotational speed and forward motion of a saw blade across a work piece. However, the system is also expandable to multiple axes of motion, resulting in the “flexible” aspect of the cut-off saw system. For example, once students gain an

understanding of the control and tuning issues for simple two-axis motion (saw speed and horizontal), the complexity of the system can be expanded to angled-cuts (i.e., two more axes of control).

The paper begins with a brief overview of the overall control system design and the relationship of the position controller to the other control tasks. We then focus specifically on the design of the position controller for the remainder of the paper. In section 3, we begin with a general description of the position control system and then introduce the experimental prototype developed to test the control algorithms in section 4. Next, we focus on the system model in section 5 and the development of the controller in section 6. Finally, section 7 summarizes our work on the position controller design, simulation and testing. The paper concludes with a discussion of the work that is being done on the CDEN design modules for this aspect of the cut-off saw project.

2. The flexible saw control system

As noted previously, this paper focuses on only one aspect of the flexible saw control system: saw blade position control. However, the overall control system consists of a number of tasks that are active simultaneously as summarized in Table 1.

Table 1. Flexible saw control tasks

Name	Description
Master	Controls start-up, operating mode, shutdown
HMI	Human-machine interface
Position	Saw blade position control
Loading	Loading of work pieces
Positioning	Positioning of work pieces for sawing and removal
Clamping	Clamping work pieces and positioning safety gates
S/D	Process monitoring and shutdown logic

From a control system design point of view, the task/state approach suggested by Auslander *et al.* [2] has been followed. For example, the control tasks listed in Table 1 represent units of work and are determined by both temporal and functional decomposition of the overall control requirement.

In this framework, tasks are then organized in a strictly sequential manner into states (i.e., the activities within a task). At this stage, it should become apparent whether the individual tasks listed in Table 1 are defined appropriately. For example, if a given task is too aggregated, it will result in parallel operations that cannot be described adequately by states (i.e., a task should only be in one state at any given time). In this case, the task would be decomposed into separate tasks. As a result, the task definition given in Table 1 is not final, as it will be refined during the control system design process.

3. The position control module

As discussed in the previous section, one of the main control tasks involves position control of the flexible cut-off saw blade. In remainder of the paper we focus on this aspect of the overall control system design and provide examples of the type of material that will be included in the position control CDEN module.

The general goal of this work is to find a suitable control strategy for a five-degree of freedom flexible saw system. Closely related to this goal is our secondary goal of using the results of this work to illustrate position control design. In particular, we have used an incremental process starting from basic PID (proportional-integral-derivative) control, advancing to PID with feed-forward, and finally adaptive PD control.

The flexible saw design is similar to a radial arm saw with the added feature of automated cutting at different angles as illustrated in Figure 2. The saw's maximum angle is designed to cut is up to 45° in either direction. The machine has three axes of independent motions, with the purpose to give a final cut of desired angle and desired size. The directions are the moving of the saw head over the arm, r , the rotating of the arm itself, θ , and the tilting of the blade, ζ . Figure 2 also show the rotation of the blade, ω , and the vertical motion of the arm, z .

Radial arm saws work on the principle of cross cutting. In cross cutting the wood is fed into a fixed position, the work piece is held tight and the saw blade traverses through the wood. The rotation speed of the blade is adjustable to handle different kinds of wood.

It is also possible to move the whole system in vertical direction to retreat the saw to home position.

Figure 1. Flexible saw axes of motion

In order to develop the position controller for this system, a four-phase design approach is being followed: (i) simulation, (ii) controller selection and analysis, (iii) experimental prototype development, and (iv) testing. Phases (i) and (ii) are basically a combination of the requirements and design phases of traditional software development cycles [2].

We begin by developing a Simulink [3] model of the controlled system. Simulink was chosen because of its close tie to Matlab [4], its intuitive graphical nature, and its capability of being used as a controller language (with a Simulink compatible controller platform).

During phase (ii) a set of test cases is executed to verify that the design satisfies all of the performance requirements. As part of this process we investigated controllers of varying degrees of complexity from simple PID control to adaptive control.

For practical purposes, we chose to use a simplified version of this system (with 2 degrees of freedom) in phases (iii) and (iv) that is used as an experimental prototype for the tests conducted for this paper (this will be described in the next section).

Since the widely used analysis and design tool (Matlab/Simulink) is used for the design of the position control system, our approach for the CDEN module development is to first use a rapid application development (RAD) approach [3] for controller design and development. In other words, the position controller is implemented on a computer that is compatible with Simulink. This allows students to clearly see the connection between the Simulink

model and the actual control of the process. However, in order to tie this project to current industrial applications and also to expand the learning opportunities of this module, we also plan to take the more traditional approach of coding the control software in a programming language that is compatible with a typical industrial target processor. In this case, our target platform is a simple PLC with a high-speed counter inputs (for the motor encoders) and analog outputs (for DC servo motor control). The target programming language is ladder diagram (LD) [5].

4. The experimental prototype

For initial control system design and testing, we chose to focus on two of the more difficult degrees of freedom, r and θ . This approach was chosen primarily to simplify the design process. In particular, the controllers designed for the r and θ axes can be extended to the other axes (if needed) and the designs can be tested in a straight-forward manner (i.e., without the added complexity of additional degrees of freedom).

In order to reduce the cost of the experimental prototype, an existing rotary system by Quanser [6] was used to produce the θ -axis motion as shown in Figure 2. This system also allowed us to take advantage of existing Quanser I/O boards. The Quanser boards have 8 analog I/O channels, 8 digital I/O channels and the ability to be run “real time” in a Matlab/Simulink environment [3, 4]. Quanser advises users to not apply a load greater than 5 kg to the rotary system. As a result, a main design criterion for the arm is to keep the weight low to minimize the maximum applied moment on the θ -axis.

Figure 2. The Quanser rotary system [6]

For the r -axis motion, three designs were evaluated as shown in Figure 3. The final design, shown in Figure 4, is based on the third design.

This design has several advantages in comparison to the other designs. The use of a single square hollow tube of aluminum reduces inertia. No pulley support is necessary at the end of the arm, which saves considerable weight. Finally, it is easy to manufacture because of the simple shapes and the fact that almost all parts are pre-manufactured.

The aluminum arm has three sliding surfaces to support the block. Teflon tape is applied to the mass for low sliding friction. At the bottom of the arm, holes are drilled to make the arm light; as well, the back the arm is extended to have a platform to attach an optional counter balance if needed.

Figure 3. Alternate arm designs

Figure 4. Final experimental prototype design

The motor support consists of two parts: the support plate and the support bases. This is mainly

done for easy assembly of the belt and mounting of the motor. The support base is a pre-manufactured U-shape that was not available in larger dimensions. To overcome this problem, six struts are used to ensure there is enough room for the pulley and the arm.

Finally, the mass (i.e., the “saw blade”) is a simple milled piece of aluminum with two threaded holes at the top to attach the belt clamp. The pulley axis at the front of the arm is mounted on the arm and slides over the pulley axis by means of sleeve bearings.

The final experimental prototype system is shown in Figure 5. The arm and rotary system are shown in the lower right of the figure. In order to interface with the Matlab/Simulink software, Quanser amplifiers and interfaces boards are used as shown in the upper left of Figure 5.

Figure 5. Experimental prototype system

Initial tests with the experimental prototype have revealed a few minor drawbacks that should be helpful when evaluating the final design of the system shown in Figure 1. For example, the position of the sliding mass is measured at the motor (via digital encoders) rather than at the mass itself. This appears to give very good results, however direct measurement would be preferable. As well, the mass has a tendency to tip slightly when moving. A fourth sliding surface could be a solution to this problem.

The belt design is quite stiff, so no low Eigenfrequencies are introduced to the system. However, play is present in the gearbox and in the pulleys, suggesting that a direct drive solution may give better results.

Finally, the Quanser system is not designed for a large arm: i.e., its support is not robust, its motor is

underpowered, and encoder resolution is not sufficient to control the arm to a higher accuracy. Clearly, this aspect of the positioning system design will have to be refined for the final prototype.

5. Modeling the experimental prototype

In order to arrive at a dynamic model of the experimental prototype shown in Figure 4, the model was divided into three parts: (i) the dynamic model of the 5 saw axes, (ii) the motor dynamics, and (iii) the dynamic model of the experimental prototype. The full details of the model are beyond the scope of this paper. However in this section we provide a summary of each part.

As noted in section 3, the full flexible saw system consists of 5 degrees of freedom. In our model, the inputs to this system are represented as torques, and for simplicity, the motor dynamics are at first left out. Each motion is modeled separately with differential equations however. It is understood that there are some interconnections between the motions.

In the experimental prototype shown in Figure 5, two servo DC motors are used – each with its own dynamics. In order to add the motor dynamics to the model, the motors are simplified with first order models. Based on the manufacturer specifications for the motors, the motor dynamics T_r (radial motor torque) and T_θ (rotory motor torque) were determined. Since the resistance in the amplifiers is very low (and unknown) it was neglected in these models.

The final step in modeling the experimental prototype involves combining the motor dynamics with a simplified set of equations for the saw system. As discussed in the previous section, the experimental prototype is a simplified version of the actual system, consisting of an arm that can rotate around the vertical axis and a mass that can slide over the arm (i.e., two degrees of freedom). Because the experimental prototype is a test system that will not actually be sawing, the sawing force is left out of the equations. The final system matrix for the experimental prototype is as follows [7]:

$$\begin{bmatrix} \ddot{\theta} \\ \ddot{r} \end{bmatrix} = \begin{bmatrix} \frac{K_{t\theta}(V_\theta - K_{e\theta}\dot{\theta})/R_\theta - (B_\theta + 2M_h\dot{r})\dot{\theta} - B_{\theta 2}\sin(\dot{\theta})}{(J_{motor}\dot{\theta}^2 + J_{arm} + M_h r^2)} \\ \frac{(K_{tr}(V_r - K_{er}\dot{r}/R_{p1})\dot{r}/R_r - B_{r1}R_{p1}\dot{r} - B_{r2}R_{p1}\sin(\dot{r}) + M_h\dot{\theta}^2 r R_{p1})R_{p1}}{J_{motor}\dot{r}^2 + J_{p1} + J_{p2} + (M_h + M_b)R_{p1}^2} \end{bmatrix}$$

where R_{p1} is the pulley radius, $B_{\theta 1}$ and $B_{\theta 2}$ are the arm viscous and coulomb friction respectively, M_h is the mass of the sliding mass, J is inertia, R_θ and R_r are the motors' terminal resistance, K_t is the torque constant, K_e is the back EMF constant, i is the gear ratio, and V is the applied voltage.

In order to get good estimates of the parameters suggested in the model some simple tests are carried out with the experimental prototype. The object was to get good estimates of the inertia and friction parameters by means of trial and error. The first test involved applying a ramp input voltage to identify coulomb and viscous friction. A very gentle slope was used, resulting in minimal influence by the system's inertia. As well, the voltage needed to be high enough to overcome the coulomb friction. The parameters were visually tuned by plotting the model and real system on the same graph. Figure 6 shows an example of the tuning process for θ .

Figure 6. Tuning $B_{\theta 1}$ and $B_{\theta 1}$

Similarly, the inertia parameters were determined by applying a sinusoidal signal to the input of the system. The amplitude and phase differences were then corrected by tuning the inertia parameters. An example of this tuning process is shown in Figure 7.

Finally, in order to verify that the model parameters are feasible for a two degree of freedom system, sinusoid inputs were applied to both axes and the results were compared with the simulated system. As expected, there are small differences between the physical system and the simulation, but in general, the model describes the physical system quite well.

Figure 7. Tuning J_{θ}

6. The PID controller

The most common way to control a system is with a PID controller [8]. For our purposes, there are three main advantages of using a PID controller: controller parameters are natural and easy to tune by hand, there is a considerable amount of experience in using PID controllers, and it is possible to implement the algorithm on cheap and widely available PLC's. Furthermore, there is the possibility to add some additional accuracy using feed forward.

One disadvantage of this approach is that a PID controller cannot be loop shaped for a multi-input, multi-output system unless it is decoupled. As well, it is not possible to take non-linearity in to account.

Since loop shaping is not possible in this case, the system's step response was used to estimate the PID gains. The objective in this case was to tune the gains to get the fastest response with a minimum of overshoot. The easiest way to do this is with trial and error. The values for the controller found by this approach for θ and r are: $P_{\theta}=200$, $I_{\theta}=0.05$, $D_{\theta}=6$, $P_r=20000$, $I_r=100$, and $D_r=20$.

The controller was tested with a reference path planner using these parameters (a description of the path planner design is beyond the scope of this paper). Figure 8 shows the error results of our tests with the experimental prototype.

When observing the behavior of the experimental prototype, it became apparent that the error is related to the position of the sliding mass. This is most likely a function of the friction in the experimental system.

In order to reduce this error, we felt it would be worth investigating feed forward. In particular, the

controller was extended with a feed forward with three parameters: the mass, the viscous friction and the coulomb friction. The parameters are tuned separately for θ and r with the input for the not-to-be-tuned state equal to zero. The parameters for the friction seem to be depended on the position of the tuned state. The inertia of the θ -axis obviously depends on the position of the sliding mass, which directly results in an error of θ . Error results for the feed forward controller are shown in Figure 9.

Figure 8. Error results for the PID controller

The results in Figures 8 and 9 appear to indicate that this system can be controlled by a well-tuned PID controller. As well, feed forward appears to be a suitable means of reducing errors in both axes. The robustness of these controllers is beyond doubt high. However, the system parameters are not all constants, so the feed forward parameters vary with time and

state. In order to get better results without further complicating the model with additional parameters and tuning an adaptive feed forward might be a solution.

As part of the position controller design, an adaptive controller was designed and tested [9]. The details of this controller are beyond the scope of this paper, however the error results were very promising. For example, initial tests resulted in errors of less than 5×10^{-5} m in the r -axis, and 5×10^{-3} radians in the θ -axis. In fact, most of the error is within 2 encoder counts, however backlash will introduce errors of approximately 4 encoder counts.

Figure 9. Error results for the PID controller with feed forward

A downside of this controller is its extreme sensitivity to external disturbances. For example, if the

system hits an object (e.g., if it is blocked by hand), the estimated parameters will show large permutation of the real values. The errors will become very high and the system will become instable.

To compensate for this problem a second adaptive controller was designed with bounds on the parameter vector. Although this controller far outperforms the traditional PID controllers described in this section, it is not recommended for a sawing application because of its extreme sensitivity.

7. Conclusions

In this paper we have provided a summary of the design process that was followed for position control of the flexible saw servo motors. Currently, this work is being transformed into a Tier II module for the CDEN network. Figure 10 provides an overview of the organization of this module.

Figure 10. Position control CDEN module organization

The details of each of these aspects of the position control module will follow the general design process summarized in this paper. This module will also have clear links to other CDEN modules for the flexible cut-off saw project. For example, we are currently investigating a PLC implementation of the controller and path planner that will tie-in with the sequential control tasks in Table 1. As well, links will exist with specific component selection and design modules such as those concerned with linear and rotational stage design, drives, DC servo motors, and position and velocity feedback devices.

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