# SERVO CONTROL OF A COAL MINING MACHINE APPENDAGE AND INTEGRATION INTO A REAL-TIME CONTROL SYSTEM (RCS) DESIGN

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## ABSTRACT

Closed-loop control of cutting drum height of a continuous mining machine (CM) using a coal interface detection (CID) sensor is described. The control is accomplished using a discrete-time Proportional-plus-Integral-plus-Derivative (PID) controller. The mining machine, sensor, and mine environment are simulated. The dynamic model of the cutting drum arm ("boom") and motors is described and a discrete time version of the solution to the plant equation of boom angle and angular velocity is derived. Cutting drum height control is placed in the context of an existing large-scale Real-time Control System (RCS) for CM control, simulation, and animation. RCS is a paradigm for defining, describing, and designing intelligent control systems developed at the Robot Systems Division of the National Institute of Standards and Technology (NIST).

## BACKGROUND

An important issue in intelligent control is the integration of servo control algorithms (*e.g.*, PID) into large-scale real-time control systems that are largely rule-based. RCS theory allows such integration [Albus 91] but more empirical examples are needed. In addition, simulation and animation are critical development tools. Integrating these tools into a large scale control system is an important challenge. Furthermore, modularity of simulation and animation will allow "plug-and-play" with real system components at any time. Effective solutions to these problems are offered in this report.

The RCS paradigm specifies hierarchical, heterogeneous levels of control where each level has a characteristic spatial and temporal resolution for each of the critical components of the system at that level. The critical components of the system are control, sensing, and world modeling. We use a sharply defined approach to RCS design characterized by task-based problem decomposition, generic software 'objects', state machines, cyclic execution, and standardized communications interfaces. This approach can be considered an implementation of the RCS described in [Albus 91], however, for the sake of clarity, we will refer to this approach as RCS throughout the paper. The cyclic execution aspect of RCS is particular apt for integration with discrete-time servo algorithms.

The focus of this work is to investigate the integration of rule-based systems with servo control systems empirically (with simulation) through a practical example. We do not seek to create a simulation system of highest fidelity nor to describe the theory of the aforementioned integration. Such issues are addressed elsewhere [Schiffbauer 92, Albus 89, Fiala 87, Wavering 88].

We focus on an application of RCS from underground coal mining which involves the control of the cutting operation of a continuous mining machine.[1] We assume the existence of variable speed control of the actuator and continuous sensor output. However, the current reality is that these mining machines typically operate under on-off or "bang-bang" style control and do not allow variable speed control. In addition, current infrared coal interface detection (CID) sensing systems provide no access to the total instantaneous infrared energy integrated over the detector array, but only provide a Boolean value specifying that a threshold amount of energy has or has not been detected. In light

[1] NIST gratefully acknowledges funding for this work from the Pittsburgh Research Center of US Bureau of Mines.

of these realities, this work is anticipating more complex systems that might in the future be available on a continuous mining machine. Such future systems would need to allow variable speed control to certain actuators and continuously variable sensor readings.

The main achievement of this project is that successful concepts and code have been developed that can easily be ported to similar applications. For example, the type of control problems encountered in the process control industry seems particularly suited to the method demonstrated.

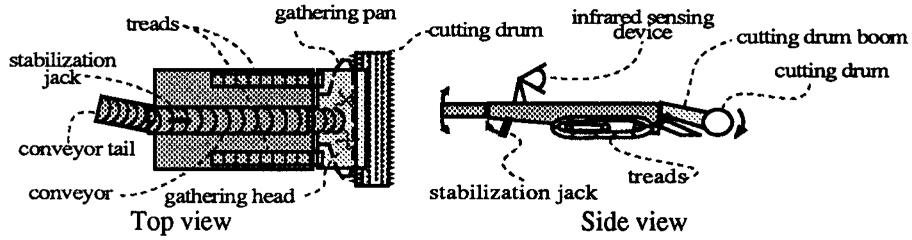


Figure 1: A continuous mining machine and appendages.

## SCENARIO FOR CLOSED LOOP CONTROL OF CUTTING DRUM HEIGHT

Continuous mining machines, as in figure 1, are common in underground coal mines. Bits on the rotating cutting drum cut into the coal seam while an on-board conveyance system moves the cut coal to the rear of the machine. There is a significant effort underway to place the operation of this machine under computer control [Schiffbauer 92]. In this regard, a particularly challenging problem is to maintain the cutting drum at the appropriate height with respect to the coal/rock interface (see figure 2) [Mowrey 92] during normal operation. This work contributes to the solution of the latter problem.

The following is a description of the basic task a continuous mining machine has to perform to extract coal from a mine. During a cutting sequence, the continuous mining machine goes through a typical cycle of operation (refer to figure 2): 1) The boom is raised with the cutting drum rotating until the drum makes contact with the roof. 2) The mining machine moves forward until it contacts the coal face. 3) While continuing to move forward, the cutting drum sinks into the coal face a distance equal to about half the diameter of the drum. 4) The cutting drum boom is lowered to the floor cutting coal all the while. 5) With the cutting drum rotating, the continuous mining machine moves in reverse to cut coal remaining on the floor.

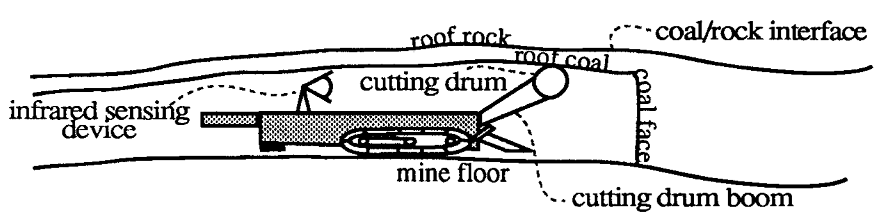


Figure 2: A continuous mining machine in a coal mine.

In order to automate the above mentioned cutting sequence (called a "sump-shear-cusp cycle"), the cutting drum must be maintained at an appropriate height relative to the coal/rock interface (see figure 2). There are roughly three modes of cutting in and around the coal/rock interface [Mowrey 92]: 1) allow some roof coal to remain (*e.g.*, if there is high impurity content in the coal), 2) remove all roof coal but as little roof rock as possible (*e.g.*,, if there is unstable roof coal), or 3) remove some roof rock (*e.g.*, if the coal seam height is low).

An actuator and angle measurement sensor are located on the boom. A coal interface detection (CID) sensor, as in figure 2, gives instantaneous analog readings of the infrared energy summed over a detector array. This energy corresponds to the total heat generated by the cutting bits on the cutting drum of the CM. This analog sensor output can be used as an indication of the depth of penetration of the bits into the coal and rock. A target value for the CID sensor output is determined *a priori* based on one of three three cutting modes. The target CID value is used to servo the height of the cutting drum using a PID controller.

In order to place the cutting cycle of the mining machine under autonomous control, we now have the following additions to that cycle: When the boom is raised and whenever the machine moves forward, the sensor values are read in real-time while the cutting drum height is servoed to the target CID value (appropriate to the cutting mode) using a PID algorithm.

## CONTINUOUS MINING MACHINE GEOMETRY

We are interested in the control and simulation of a specific continuous mining machine (CM) called the JOY16CM[2]. Figure 3 gives the relevant definitions and lengths required for cutting drum height control and simulation.

From the definitions of figure 3 we see that the distance from the mine floor to the top of the cutting drum is $d_1 + d_2 \sin\theta(t) + d_3$ and the distance from the turning center of the CM to the center of the drum is $d_4 + d_2 \cos\theta(t)$.

Given knowledge of the world coordinate position and orientation, $(x, y, \psi)$[3], of the CM, we can now determine the parameterized equation, in world-centered coordinates, for the line segment that defines the top of the cutting drum; the part that makes contact with the mine roof. This is critical for CID sensor value simulation, since we need to compare the height of simulated mine roof surface at the line segment of contact with the cutting drum in order to develop the simulated CID sensor value.

Referring to figure 3, if $t$ is time, $X'(t)$ is a point in CM-centered coordinates, $X(t)$ is a point in world-centered coordinates, and $\mathbf{r}(t) = (x, y)$ is the world position of the CM, then $X(t) = \mathbf{R}(t)X'(t) + \mathbf{r}(t)$,

$$\text{where } \mathbf{R}(t) = \begin{bmatrix} \cos\psi(t) & -\sin\psi(t) \\ \sin\psi(t) & \cos\psi(t) \end{bmatrix}.$$

The points we want on the line segment representing the top of the cutting drum are

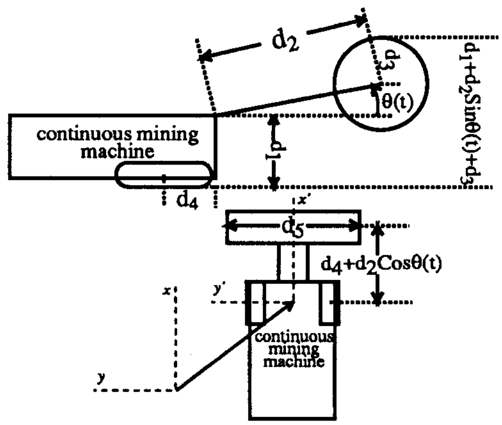


Figure 3: CM dimensions

$X'(t,s) = (d_4 + d_2 \cos\theta(t), d_5 s - d_5/2)$ for $s \in [0,1]$. If we are given $X'(t,s)$ and $\mathbf{r}(t)$ we can find the same line segment in world coordinates, $X(t,s) = \mathbf{R}(t)X'(t,s) + \mathbf{r}(t)$.

## SIMULATION

One goal of this work is to simulate actuators, sensors, and the mining environment to the extent required. Furthermore, we wish to learn how and in what way such simulation can be modularized and integrated into the existing continuous mining machine RCS control code [Horst 93]. High fidelity simulation is of lesser importance.

In the interest of modularization, a separate 'file' is created for each item being simulated. Each file has the standard RCS read, compute, write format for communications [Quintero 92]. Each section will conclude with a processing flow description of that particular file.

## SIMULATED BOOM DYNAMICS

In this section we focus on actuator simulation. The actuator is the rotating boom and its motor. A second order servo system (a positioning system) is chosen as an adequate model of the boom and its motor. With this model assumption, the second order dynamic equation of angular motion of the boom is of the form [Phillips 84],

$$\ddot{\theta}(t) + a\dot{\theta}(t) = bu(t), \qquad (1)$$

where $\theta(t)$ is the angular position of the boom and $u(t)$ is the control voltage driving the motor. If we let $x_1(t) = \theta(t)$, $x_2(t) = \dot{\theta}(t)$, $\mathbf{x}(t) = (x_1(t), x_2(t))$,

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[2]The US BOM is using JOY continuous mining machines as testbeds for computer controlled mining research. The JOY16CM is manufactered by JOY Manufacturing Corp and reference to it does not imply endorsement by NIST or the US BOM.

[3] $\psi$ is defined as positive, counter-clockwise from the $x$-axis.

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix}, \text{ and } B = \begin{bmatrix} 0 \\ b \end{bmatrix},$$

we get the differential plant equation in state space form,

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + Bu(t). \qquad (2)$$

Since we intend to do the control using discrete sensor sampling (sampling period of $h$ seconds) and discrete control values, we need to express the solution to (2) in discrete form. The solution requires that some matrix coefficients,

$$P = e^{Ah} = \begin{bmatrix} 1 & a^{-1}\left(1-e^{-ah}\right) \\ 0 & e^{-ah} \end{bmatrix} \text{ and}$$

$$G = \int_0^h e^{A\sigma} B d\sigma = \frac{b}{a^2} \begin{bmatrix} ah - \left(1-e^{-ah}\right) \\ a\left(1-e^{-ah}\right) \end{bmatrix}$$

be computed [Åström 84]. The discrete-time variation of constants formula results,

$$\mathbf{x}_{k+1} = P\mathbf{x}_k + Gu_k, \qquad (3)$$

and is iterated to update the state given a sequence of control inputs, $u_k$, sampling period, $h$, and particular values for $a$ and $b$ appropriate to the motor and boom dynamics.

A processing flow description of the cutting drum arm actuator simulator is as follows [Quintero 92]:

Preprocessing: read boom control voltage, $u_k$, and the current boom angle and angular velocity (the state, $\mathbf{x}_k$).

Decision processing: update boom angle and angular velocity using (3).

Post processing: write out the updated boom angle and angular velocity ($\mathbf{x}_{k+1}$).

# SIMULATED BOOM ANGLE SENSOR DYNAMICS

A cutting drum boom angle measurement sensor is also simulated. It can contain any knowledge of the noise and dynamic characteristics of the particular sensor being simulated.

A processing flow description of the cutting drum boom angle measurement sensor simulator is as follows:

Preprocessing: read current boom angle.

Decision processing: simulated sensed boom angle using past values and knowledge of sensor noise profiles.

Post processing: write out the new sensed boom angle.

# SIMULATED COAL SEAM HEIGHTS: A RANDOM WALK SURFACE

To effectively demonstrate cutting drum height control, we need to simulate the natural variations in height of a coal seam. For our purposes, it is sufficient to simulate a coal seam by a single surface representing the seam height. To do this we employ the concept of a random walk surface.

A random walk surface is generated from a pair of 1D random walks. If $(x_i, y_j)$ are discrete positions in the coal mine, let $v_1(x_i)$ represent the first random walk sequence as in figure 4 and $v_2(y_j)$ represent the second random walk sequence as in figure 4. Then the random walk surface simulating the seam height is simply, $v_1(x_i) + v_2(y_j)$, an example of which is figure 5.

It is useful to express this surface in functional form so that one can simply input any position $(x, y)$ in the mine and get a roof height for that value. In order to accomplish this, we form an interpolation function based on sampled points from each of the two 1D random walks. The sum of the two values forms the random walk surface. We were able to express this surface functionally, in terms of coefficients relating to the Newton interpolation formulae using both forward and backward differences [Volkov 86].

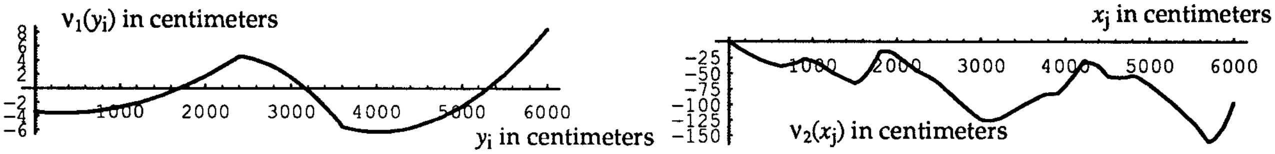


Figure 4: One dimensional (interpolated) random walk functions

## INFRARED COAL INTERFACE DETECTION MEASUREMENT SIMULATION

We must also simulate the coal interface detection (CID) measurement value based on the simulated roof height function stored in the world model and the current height of the cutting drum. The value of the infrared CID sensor will vary continuously but not necessarily linearly with closeness of the cutting drum to the coal/rock interface (we expect the actual relationship to be piecewise linear, i.e., constant in air, approximately linear with steeply positive slope in coal, and approximately linear with even steeper slope in rock). However, for simplicity, we will assume a linear relationship between the current CID value and the difference between the cutting drum height and the roof height. The expected non-linear relationship specifies a measurement equation that is a non-linear

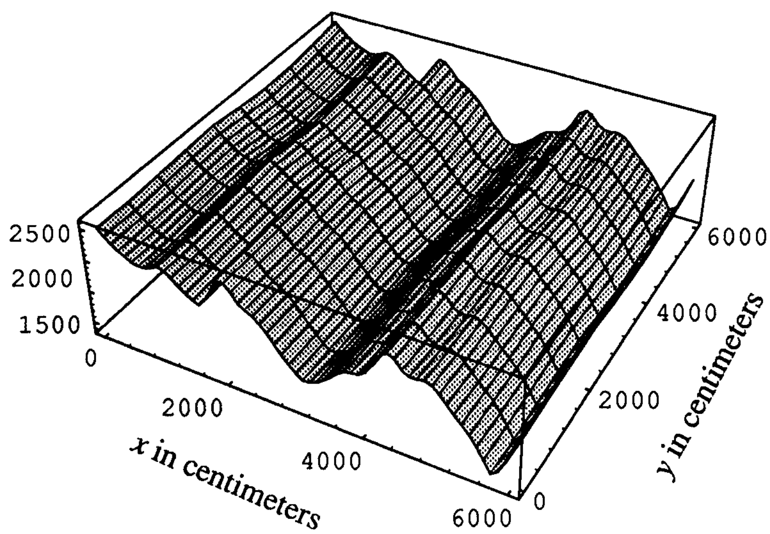


Figure 5: seam height function (in centimeters)

function of the state vector, $\mathbf{x} = (\theta, \dot{\theta})$. This is a legitimate argument for the aptness of using PID control (with or without simulation), since a PID controller does not require a linear measurement model.

A processing flow description of the CID sensor simulator is as follows:

Preprocessing: read continuous mining machine (CM) geometry values such as current position and orientation, the cutting drum boom angle, and the cutting mode.

Decision processing: based on the cutting mode, compute a CID sensor target value. Based on the position, orientation, and geometry of the CM, compute the position at the cutting drum, the height of the drum, and the simulated coal seam heights across the top of the cutting drum (using the interpolated random walk surface). Based on the cutting mode compute the new CID sensor value.

Post processing: write out the new CID sensor value and CID sensor target value.

## PID DEVELOPMENT

We postulate a PID filter that outputs the updated cutting drum motor control value from past and present error signals:

$$u_k = K_p \varepsilon_k + K_i \sum_{j=k-3}^{k} e^{-c(k-j)} \varepsilon_j + K_d(\varepsilon_k - \varepsilon_{k-1}) \quad (4)$$

$K_p$, $K_i$ and $K_d$ are the control parameters in (4) representing the proportional, integral, and derivative gains. An error signal, $\varepsilon_k$, = current CID value – target CID value is formed at each time step, $k$. The error signals, $\varepsilon_k$, $\varepsilon_{k-1}$, $\varepsilon_{k-2}$, and $\varepsilon_{k-3}$, are used by the PID controller to generate the next control value, $u_k$, which is a voltage value sent to the motor responsible for rotating the cutting drum boom (see figures 1 and 2). The commanded control value is affected by the amplitude, frequency, and phase characteristics of the error. Note that the integration term of the controller has an exponential forgetting factor with parameter, $c$. We discovered that different PID gain constants were needed when the boom was raised than when the machine was moving forward.

The rule-based portion of the RCS control design for the continuous mining machine (CM) executes the PID function only when the CM is raising the boom or moving forward during a cutting cycle.

A processing flow description of the PID controller function is as follows:

Preprocessing: read current sensed (or simulated) CID sensor value and CID sensor target value. Form error signal: CID sensor target value – CID sensor value

Decision processing: compute the new cutting drum motor control value based on error values using equation (4).

Post processing: write out new control value and save old values.

# INTEGRATION INTO AN RCS DESIGN

RCS is a real-time architecture and design methodology for intelligent large-scale control systems [Albus 91, Quintero 92]. A large-scale RCS design exists for continuous mining machine (CM) control [Horst 93]. The problem addressed in this section is how we integrated the cutting drum controller/simulator into the current large scale design. Such integration is summarized in figure 6.

The integration of the various simulation modules (actuator, sensors, and coal seam height) into the existing RCS for CM control was performed in the following manner. The existing RCS design was stubbed out with dummy simulators that acted as place holders. Simultaneously, the compute and decision algorithms that form the heart of each module (simulators and the PID controller) were developed and tested separately using mathematics software. Each of the modules were translated to 'C', recompiled, and tested individually. Finally the modules were added one at a time to the existing RCS design. The animation portion of the system (see figure 6) proved to be a valuable tool for debugging the various modules.

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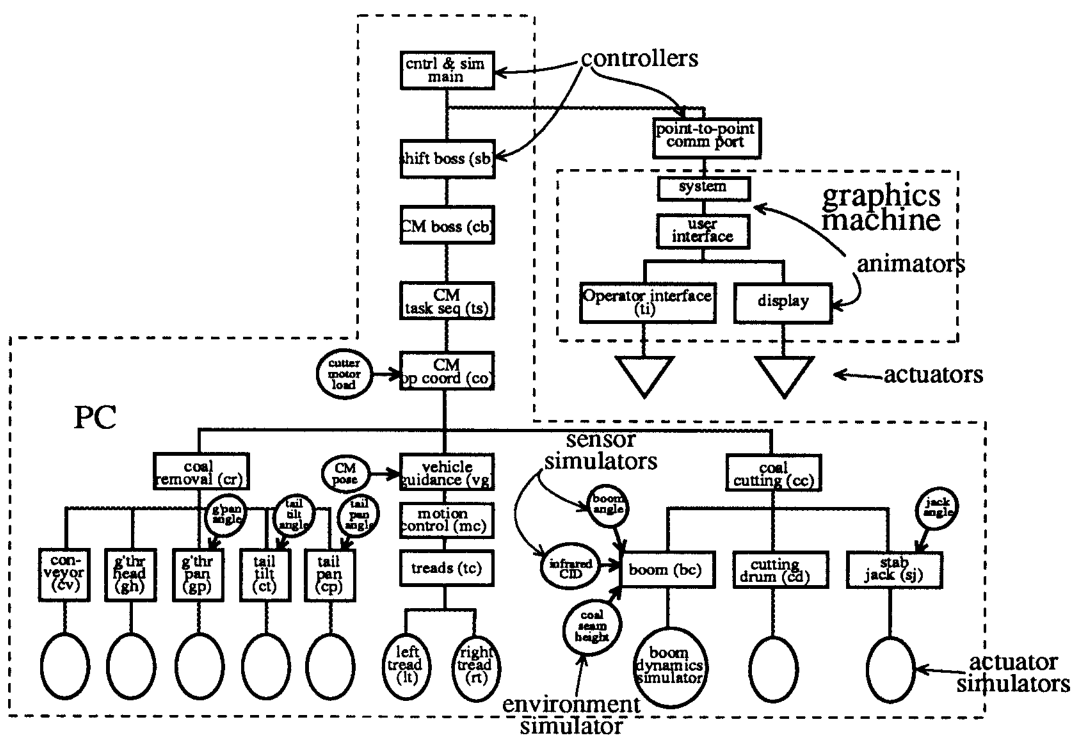


Figure 6: Integration of various types of simulation into RCS design

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